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Inferring the Behavior of Households from Remotely Sensed Changes in Land Cover

Current Methods and Future Directions

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For the past 15 years, thanks in great part to the availability of 30-meter resolution Landsat Thematic Mapper (TM) digital data, a number of researchers have been able to carry out studies of land use and land cover change, focusing on issues such as landscape ecology, deforestation, and desertification and more recently, exploring the connection between climate change and health. Most of these analyses have focused on meso- and macro-scales with spatial resolution that is either global, national, or macro-regional (e.g., Amazon Basin, Southeast Asia). However, in the past 5 years a small community of scientists has begun to explore empirically the possibilities of more spatially detailed work that permits the examination of processes taking place at the household level. This chapter reviews these efforts, giving particular attention to the methods used: how they contribute to theory-building and methodological advances in a number of disciplines wherein the focus of research is on households, families, and other small social units.

Inferring the behavior of households from remotely sensed data is not commonplace—but it is now within reach. The spatial resolution of satellite data is improving, and so are the tools used to manipulate these data. These on-going improvements also benefit from the increased temporal frequency of data acquisition that improves the possibilities for the assemblage of finely grained spatial and temporal data. A number of important ethical challenges are presented by this opportunity: who should have access to these data, how should the behavior of individuals and households be protected, and what is appropriate and inappropriate use of these behavioral inferences? The scope of this chapter does not address these questions, but readers should take time to reflect on the ethical implications posed by this growing capacity to link spatial data to the behavior of households and communities. A number of expert meetings are planned for 2004 that will try to bring scholarly order and reflection to these issues. While it may be desirable to carry out research at the finest grained scale possible, given the explicitness of spatial information, research results may need to be aggregated to protect the confidentiality of the subjects.

This chapter reviews current approaches taken by a number of investigators examining urban areas, rural areas where people live in villages and commute to their landholdings, and rural areas where people reside on the land they use. Each of these contrasting settings presents distinct challenges to linking households to land cover change and for inferring the behavior of households using remotely sensed data within a geographic information system (GIS). A detailed discussion of concept, methodology, and empirical findings is based on approaches developed by our research group in the Brazilian Amazon. In this work we have linked demographic, social survey research to a time-series of Landsat TM, multispectral scanner (MSS), and aerial photography to construct a temporally and spatially fine-grained analysis of changes in land cover at both the landscape and individual property scales so as to achieve accurate inferences about the behavior of households. This accuracy is possible because we can check our inferences against the survey research data collected from households.

Methods for Studying Land Use in Urban Areas

Most researchers studying land use and land cover change have ignored the role of urban areas in driving land cover conversion and bringing about environmental change. The data from orbital satellites are well suited for providing information to analyze a number of important environmental changes. However, there is very little agreed upon with regard to the methods for systematically characterizing urban land cover and examining land use in an urban context. Part of the challenge is defining the difference between urban and rural so that change can be adequately assessed (e.g., the expansion of urban areas into peri-urban and rural landscapes over time accompanying population growth and development). Land cover is the most important source of anthropogenic change on the planet (Turner et al. 1994; Lambin et al. 1999). The conversion of forest and grasslands to agropastoral uses has received the most attention by scientists, because of its link to deforestation, biodiversity loss, and carbon emissions (Walker and Steffen 1997).

Much of the research conducted by the remote sensing community in the urban context has been concerned either with management and planning or with the general problem of urban expansion (Jensen 1983; Jensen et al. 1994). This focus on urban and suburban expansion (and sprawl in the North American context), though implicitly connected to larger concerns about the environment and the consumption and exploitation of material resources and energy, has not been explicitly linked to regional land use and land cover conversion processes occurring on the periphery of urban centers or their surrounding regions, particularly in the developing world. There are a few cases where urban expansion and influences upon the urban fringe have been analyzed. However, these analyses have focused on North American (Canadian), European, and Chinese locations (examples include, respectively, Treitz et al. 1992; Antrop 2000; Wu 1998) that have a long history of dense urbanization. These studies focus on the general measure of urban expansion, rather than on regional land use and conversion.

This is a serious oversight, albeit partly produced as a consequence of technological limitations. All around the globe, including areas like the Amazon region, a process of rapid urbanization is underway. Urban areas are the loci of human activities, and urban interests increasingly drive rural land cover change (Browder and Godfrey 1997). Urbanization concentrates populations, and this results in significant impacts on land, water, materials, and energy. Thus, to understand land cover change, one must study the process of urbanization itself.

Currently there is no standardized description of urban land cover, nor is there a generally accepted definition of a city (Davis 1969; Whyte 1985; Lambin et al. 1999; Foresman et al. 1997). In Peru, urban areas are defined as "populated centers with 100 or more dwellings," while in Japan, urban is defined as places having 50,000 or more inhabitants (UN 1994). There is a mismatch between administrative boundaries and actual built-up land, and the human population is therefore over- or under-represented depending on city boundaries (UN 1994). This problem is a result of administrative boundaries routinely lagging behind urban growth and areal expansion. Despite the lack of a globally recognized definition of a city, it is possible to determine urban characteristics of land cover and land use using remotely sensed imagery gathered from satellites and airplanes. Land cover classification approaches that rely on Landsat MSS and TM imagery (79-meter and 30-meter resolutions, respectively) often fail to capture urban land cover because the resolution is too coarse for capturing adequately the complexity of the urban landscape. This is also due in part to the use of image classification techniques that rely primarily on the spectral information in the image without adequately incorporating texture or spatial structure. The primary limitation in the developing world, however, is access to adequate financial resources and technology to acquire and make use of detailed remotely sensed imagery. High spatial-resolution imagery in the form of aerial photographs has been available for close to a century in some parts of the world but is costly to acquire and process. In the past forty years, with the advent of remotely sensed satellite imagery, it has become possible to classify and analyze much larger portions of the earth's surface. Concurrently, a greater range of classification and accuracy has become possible as a result of technological improvements that have increased the range of observations of physical properties of the objects/surfaces being imaged. These advantages result from the use of a wider range of the electromagnetic spectrum—beyond normal human vision—and the use of radar and laser systems (see, e.g., textbooks on remote sensing and image analysis by Jensen 1996 and 2000). At the same time that advancements have been made using a variety of methods to determine the physical properties of the earth's surface and the objects on it, there have also been improvements in the resolution or grain at which those properties can be observed. Cowen and Jensen (1998) suggest that in order to capture better than a USGS Level 1 urban classification[1] it is necessary to use imagery with a ground resolution of better than 20 meters and for many urban applications, better than half a meter. For information on appropriate spatial and temporal scales see Cohen and Jensen (1998, 167). They also state that remote sensing can only provide a suggestion of the details of human activity.

To capture the complexity of the urban landscape, it would be useful to create an urban-rural gradient or transect of the transitions from one condition to the other (including urban areas that may end up over time as abandoned and reclaimed for other uses). One can begin such an approach by defining the elements that characterize urbanization (McDonnell and Pickett 1990) and standardizing them across world regions (Whyte 1985). In doing this, there are considerable advantages to using remote sensing. However, the use of remote sensing in capturing urban elements is challenging, particularly in representing accurately the complex mosaic of human modifications and built structures (Zipperer et al. 2000). Urban areas vary in terms of density of dwellings, the three-dimensional structure of buildings, the types of construction materials used, and the amount and type of vegetation present, among other factors.

The first requirement of developing standardized methods is to represent the range of physical, biological, and socioeconomic variations present (Moran 1995). In urban areas this means coming up with a gradient of cities that combines population size, spatial settlement patterns, and differences in settlement history. Population size and differences in settlement history can be obtained largely from census and archival research and help in defining the number of urban area types that might be desirable to characterize. The spatial settlement pattern, particularly as it relates to the type and distribution of land covers, can probably best be done by combining Landsat TM with aerial videography. Aerial videography captured in digital image format can be made into a mosaic, visually analyzed, and then classified using automated methods to compare with TM imagery (Hess et al. 2002). This can be further improved with the use of either Quickbird or IKONOS imagery[2] (the former with 61 cm spatial resolution in panchromatic and 2.4 m in multispectral, and the latter with 1 m panchromatic and 4 m multispectral) should funds be available for this detailed imagery. The drawbacks of using aerial videography and the high spatial resolution IKONOS and Quickbird imagery are the cost, storage, and processing requirements.

Aerial videography can help to identify the components of urban land cover precisely. The better-than-one-meter resolution of aerial videography permits a refined observation of components of the landscape, such as types of roofs, number of trees in backyards, quality of roads, size of buildings, types of infrastructure, and water bodies. These observations can be used to build a library of reflectance spectra for urban materials. It is then possible to derive Vegetation-Impervious Surface-Soil (VIS) fractions (Ridd 1995) for each TM pixel using spectral mixture analysis, eventually resulting in the development of maps of land cover change based on the VIS components (Powell et al. 2001; Madhavan et al. 2001). This approach seeks to address the problem of spatial resolution associated with that Landsat TM. Its 30-m pixels capture multiple urban surface materials; hence each pixel is made up of heterogeneous urban structures that hide the distinct urban components (Roberts et al. 1998). Selecting endmembers for spectral mixture analysis is particularly problematic in urban areas because of the great variety of materials used in the construction of buildings, roads, and other urban surfaces. Simple spectral mixture analysis will not model successfully the components of the urban landscape. A variation of spectral mixture analysis that allows each pixel to be modeled as different end member combinations (known as multiple end-member spectral mixture analysis) seems to overcome this problem (Roberts et al. 1998). Urban materials can then be grouped minimally into three classes: vegetation, impervious surfaces, and soils. These quantities can be compared regardless of local environment or construction materials (Ridd 1995). This approach eventually permits the comparison of urban land cover change with the socio-economic structure of cities over time and space. If a sufficiently detailed time series is constructed (Powell et al. 2001), it is then possible to develop inferences about the behavior of households in and around their buildings and other structures of land cover. This approach is advantageous in that it provides a gradient of change that can be used to determine transition from urban to rural, although this is also dependent on the land cover of the surrounding region.

One approach to linking urban households to the satellite imagery at a cluster-of-households level is to infer the behavior of households by generating historical maps of change in the urban-rural gradient. This can provide valuable information about the transformations experienced by households in urban areas over time. For example, if one takes a small urban area in the Amazon frontier, one will see thatch roofs dominating cover of houses, with only a few tile roofs indicative of the elite families, from the period before growth and development that began in the 1970s across that region (Moran 1993; Wood and Perz 1996). After that, one sees replacement of many of the thatch roofs with corrugated fiberglass, and the thatch roofs moving to the outskirts in what may be called shantytowns. Over time, one will see these shanty towns improve in quality, and this can be measured by the shift in materials used in houses and roofs, by the paving of roads, by the dispersion of warehouses from the riverside towards the roadsides, and by the planting of trees on promenades and in large patios surrounding the houses of the elite. These too will be more numerous and move towards peri-urban areas and away from the river toward the road, to indicate the shift in economic infrastructure that marks the importance of road transportation and the decline of river transport. As the urban area grows and the number of warehouses increases, indicating the growth of commerce, one can see shifts in land cover in the rural areas. This may be measured by the shift from smaller to larger properties, and from subsistence cultivation plots to larger pasture-dominated ranches—a preferred form of land use by absentee owners living in the city. The measurement of these shifts is possible using the techniques mentioned above, and inferences about economic development, population change, and social stratification can be derived with reasonable accuracy.

Since videography is a costly and intensive effort, it may be possible and more appropriate in some cases to use coarser analytical methods, including remote sensing image analysis and GIS spatial analysis techniques, to identify and characterize larger peri-urban landscapes and to evaluate their internal dynamics, as well as their relationship to urban cores and to the extensive rural and possibly even wilderness/frontier landscapes that they provide linkages between. Below, we provide one example of a method that uses available classified Landsat TM imagery for determining a general transition or gradient in land use and land cover, in this case for the city of Altamira, in Pará State, Brazil (Figure 2.1). This method uses previously produced land use/land cover classifications (LULC) (Brondizio et al. 2002) that have been simplified to five classes and that use 1-kilometer buffers from a derived settlement/urban center to extract the percent of each class for each buffer zone. The classes were generated using data derived from a 1996 TM image with 30×30-meter pixels using a land use/land cover classification that was developed for the larger rural and forested region to the west of the city. Training samples were collected to inform the spectral classification of the Landsat TM image for 1996. The variety of classes was reduced to provide for a simplified analysis. The metrics for each of these zones are provided in Table 2.1, and Figure 2.2 provides a graph for easier visualization. This form of exploratory analysis

Table 2.1. Altamira: Percent land use/land cover for 8 1-kilometer buffer regions (1996).

km	Mature Forest	Secondary Succession	Bare Soil and Pasture	Water	Urban
1	12	14	1	1	72
2	14	21	11	9	45
3	23	20	12	20	26
4	29	22	21	15	12
5	42	23	24	14	0
6	42	24	19	15	0
7	42	26	19	14	0
8	34	33	20	13	0

is not complex, but it does clearly show a transition in land cover from majority urban near the urban center (as expected) to larger percent cover in mature forest and secondary succession forest further out from the urban center.

The two figures and the table do not show anything beyond what one would expect in a predominantly rural region where the city chosen for description is the dominant mercantile center. What the table and figures illustrate is that it is possible to quantify relationships between the different LULC classes. This method does not identify explicitly individual components in the heterogeneous landscape that most urban areas are, but it does provide a simple and effective method for determining general changes in land use and land cover as one moves from the center of an urban area or settlement to its periphery, or beyond. Simple descriptive measures of land use and land cover classes for each buffer can be used for comparative analysis between buffers, across time, and across sites. The urban core is within the first 1-kilometer buffer, and in this buffer the percentage of the landscape classified as urban is 72 percent. This figure quickly drops to 45 percent, 26 percent, and then 12 percent for each successive buffer of 1 kilometer out from the urban center. The complexity and interaction of land cover classes increases between 3 and 5 kilometers out from the center. In this region there is a complex mix of urban, forest, secondary succession, and pasture and bare soil. It is in the area of Altamira's urban fringe that one can pursue questions about spatially explicit patterns and processes. Multiple dates can provide a model of the trajectory of urbanization and landcover change over time and space that can be related to general events in the economy and in regional development.

There are problems associated with the arbitrary nature of buffers that are not linked to any specific phenomenon. The total area within each region created from the concentric circular buffers is not equal, nor is the perimeter. Therefore, even if percent measures are used, the regions may not be comparable. Despite such problems, this example provides a conceptualization of methods and ideas that can be used to develop gradients or transition measures on the impact of urbanization and its relationship to peri-urban and rural landscapes on land use and land cover change. This method provides general information about the landscape that may be useful in deriving parameters for more complex analyses. Using similar methods for other cities in the Amazon and around the world would provide for cross-comparison.

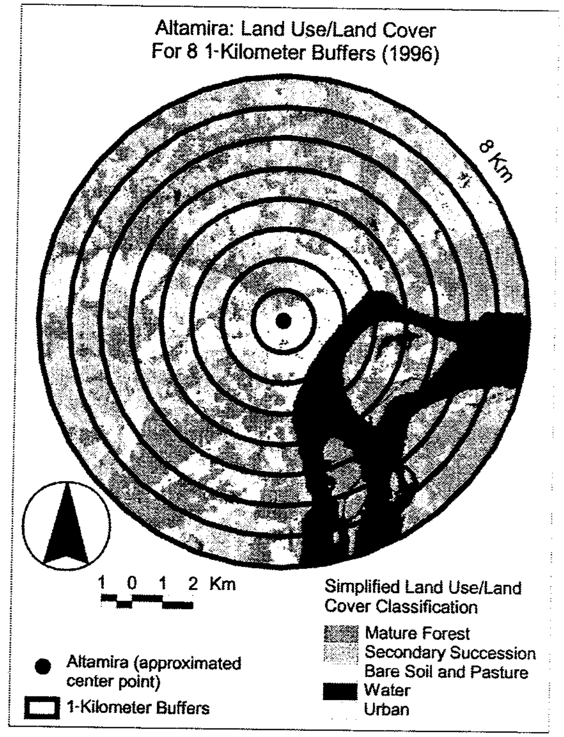

Figure 2.1. Map of Altamira: land use/land cover for eight 1-kilometer buffer regions for 1996.

It is clear that more complex but similar methods may be appropriate for characterizing, describing, and explaining the dynamics of land use and land cover change for urban-fringe and peri-urban regions. Though the method provided above is not complex, it does lay the groundwork for more complex analyses. Analysis of land use and land cover in urban areas, along the urban-fringe and urban periphery, and analyses that incorporate holistic objectives, seeking to characterize and model processes of urbanization in relation to the surrounding landscape, would include methods that incorporate a larger variety of LULC classes and buffering techniques that take into account the shape and the population density of urban centers. Frequently, in spatial analyses that use buffers, the buffers are arbitrary (as presented in the example above), or they are derived using linear distances from a given point, line, or polygon. Other buffer methods are possible, which use shapes that take into account human or biophysical processes, including ellipses that incorporate directional processes, and region boundaries that are produced using raster rule-based boundaries that incorporate topography (or a cost distance) and natural barriers (rivers, water bodies, cliffs, etc.) (for examples, see Evans 1998). Alternative methods for quantifying LULC for the regional landscape would also include alternative spatial sampling procedures, such as hexagonal, triangular, or rectangular (square) grids of predetermined size, providing a strategy that compares many like-size regions rather than the unequal areal extents

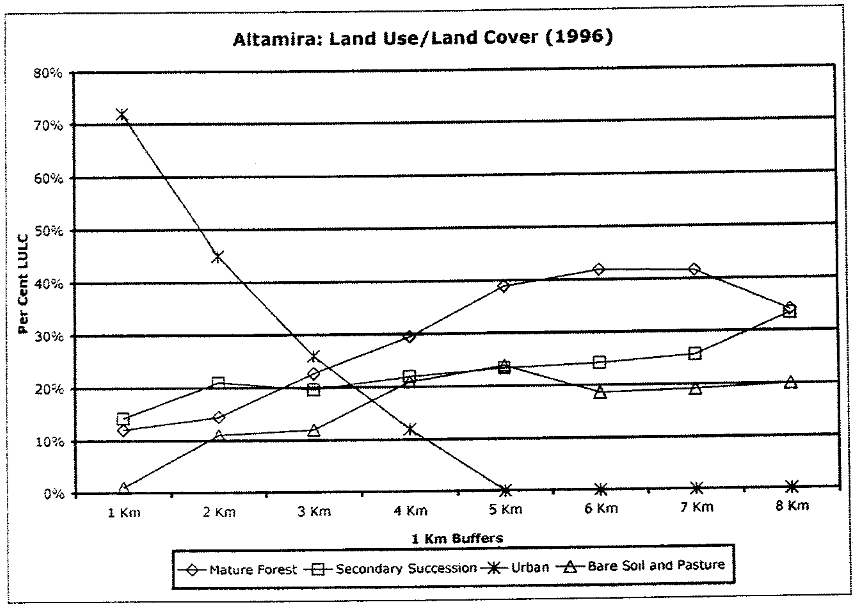

Figure 2.2. Graph of Altamira: land use/land cover for eight 1-kilometer buffer regions for 1996 as percent of cover class.

that are frequently produced by using uniform buffers. Alternatives also include the use of different classification techniques that produce change-based LULC classes, rather than hard single-time-period classes or classifications that are based on fuzzy or gradient classes (continuous rather than discrete). Methods should also be borrowed from landscape ecology that derive landscape fragmentation metrics for landscapes, individual classes, and patches. Methods for deriving landscape fragmentation metrics have found great utility in landscape ecology (Turner 1989; Baker and Cai 1992) and should also be considered for use in the analysis of urban-rural landscape processes. A final methodological component for the improvement of and incorporation into such analyses is the use of texture or spatial structure. Much LULC research uses remotely sensed imagery that is classified by methods that rely on spectral differences but that do not take into account very well the texture or overall spatial structure of the data. Two ways to address this are to (1) incorporate image (spatial) texture derived from neighborhood-based (kernel) calculations and (2) include geostatistical metrics derived from spatial variation in the data via the use of the semivariogram. Incorporation of texture is important in urban regions because of the spectral heterogeneity that is often encountered in such regions, but it has also recently found application in forest analyses. The semivariogram is used most frequently for modeling continuous (and often sparse) data; however, recent applications have used it for modeling differences between urban and non-urban regions from remotely sensed imagery (Brivio and Zilioli 2001). These methods, when incorporated with methods already developed that

use image-derived data and spatial data, such as census tract or block group population and household structure (i.e., Cowen and Jensen 1998), provide many opportunities for improving the description and modeling of urban, urban-rural, and environmental change.

Methods for Studying Rural Areas Where People Live in Villages

One of the most common settings one finds in rural communities involves populations living in villages and commuting to nearby fields. Since their residential location does not have a one-to one relationship to the property (see Figure 2.3B), this presents particular problems to understanding how households use the land. A particularly well-studied site can serve to illustrate this type of situation and some of the methods that have been used to address this challenge. A team of sociologists, geographers, and demographers has been studying Nang Rong District in Thailand since 1992. The district, an area of 1,300 square kilometers, has an undulating landscape cultivated with paddy rice in the lower elevations and with manioc in the higher elevations to the east. The study began by linking GIS to survey data. It then acquired several Landsat images to evaluation of the land use and land cover changes in the region.

One important strength of this project in Thailand was the thorough development of spatially explicit social survey data. This approach is recommended for similar studies that link households to plots. These surveys followed up individuals, households, and villages using a community profile, a household survey, and migrant follow-ups. The village profiles provide information about cropping, use of fertilizer, water sources, and deforestation that serve to cross-check the satellite image analysis. It also provides a basis to decide when a village should be treated alone, and when it makes more sense to treat it as part of a cluster of villages due to exchanges and interconnections (Walsh et al. 1999; Entwistle et al. 1997). The household survey consisted of a complete household census in each of the 51 villages, which included: demographic information, visits and exchanges between households, migration patterns, plots of land owned and rented, use of agricultural equipment, crop mixes, planting and harvesting behavior, and debts. These data have a lot to offer when used in conjunction with remotely sensed data. Aggregated to the village level, the household data offer a contrasting perspective to the satellite image analysis and the community profile. The timing of planting and other activities further informs the interpretation of spectral data from Landsat images.

This kind of prospective research design allowed the investigators to link a 1984 survey to a 1994 survey by finding all households from the former in the latter. This allowed the 51 villages to be studied for population change in population composition (age, education, occupation, assets) over the 10-year period. Most importantly, it allowed the examination of population processes prospectively, i.e., examining the out-migration of young adults in relation to the availability of undeveloped land, the fragmentation of land use, and competition from other villages (Rindfuss et al. 1996). The final component of the study followed migrants from 22 of the 51 villages, chosen randomly.

The Nang Rong situation has the locations of household residences in villages and therefore does not provide any indication about the location of farms for households;

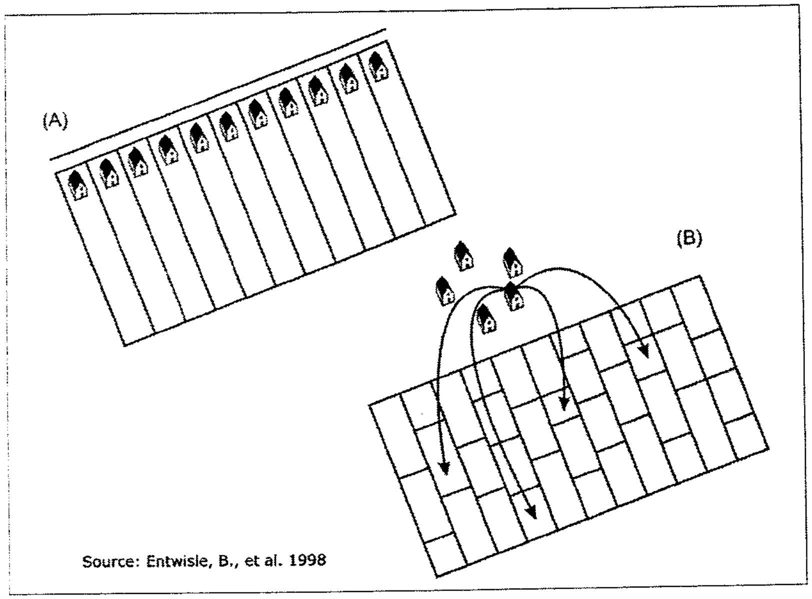

Figure 2.3. Nang Rong household and farm property relationship (adapted from Entwisle et al. 1998) is represented in (B).

further, single households often farm multiple plots that are scattered throughout the area. Trying to locate the coordinates of every single one of those multiple plots is prohibitive for investigators. This leads to the use of the village as the unit of observation. The population surveys at the household and village level are represented in the GIS as discrete point locations at the village centroid. Such a spatial representation is correct, given the nuclear nature of the settlement pattern. Integration of social and environmental data requires transformation whereby a polygon representation is used to denote the pattern and variability of landscape conditions associated with discrete village locations. This transformation requires defining village boundaries, a complicated issue where political boundaries change over time.

The investigators generated radial buffers around the nuclear village centroids at distances of 2 and 3 km. This is a simple solution that takes into account the fact that villagers rarely walk further than that to fields, allows for village overlapping boundaries, and represents well the village settlement concept. Figure 2.4 illustrates the 3-km buffers for the 51 villages overlaid on a 1993 TM image. The figure makes clear that villages may be competing with one another for land. Other approaches can also be used in setting village boundaries, such as Thiessen (Thiessen and Alter 1911) polygons, population-weighted Thiessen polygons, and Triangulated Irregular Networks (TINs) (Entwistle et al. 1998). Thiessen polygons are polygons that are derived from the spatial relationship between points distributed over a surface. They are derived by a mathematical operation that divides the space between points and connects the lines that result from this division. This results in an optimal division of a region based upon

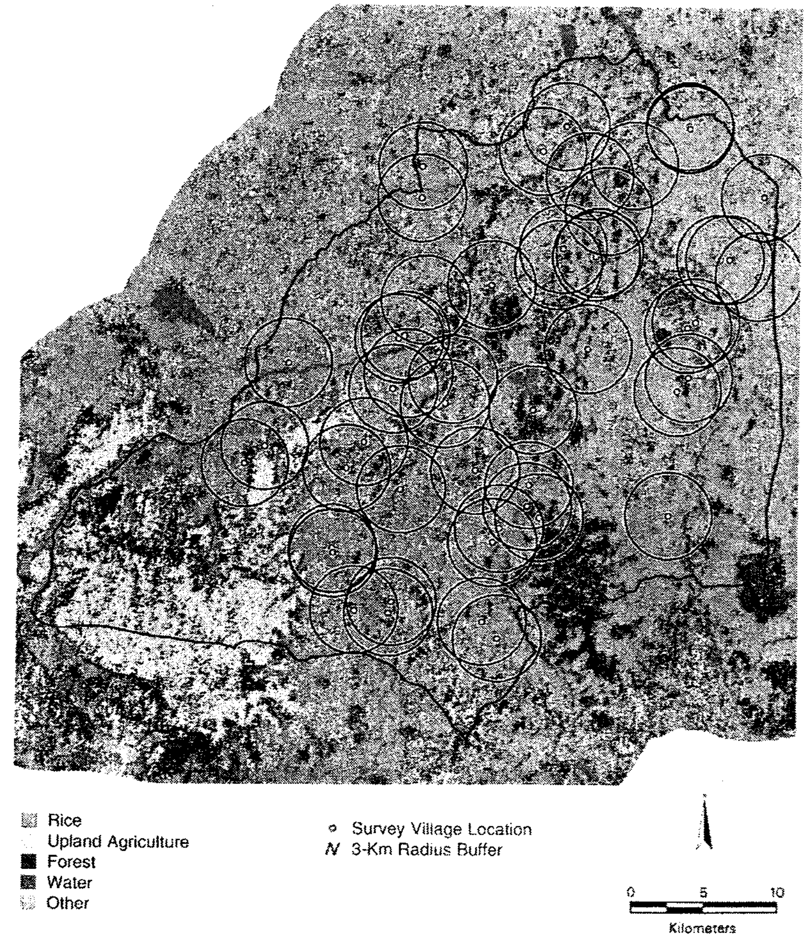

Figure 2.4. Land use/land cover with survey villages and 3-km buffers, Nang Rong, Thailand, 1993.

the points distributed within it. Such approaches produce non-overlapping and irregular village boundaries. Figure 2.5 illustrates the use of a Thiessen polygon approach using the same 1993 TM image. This kind of analysis allows one to make reasonable inferences about the behavior of households. The overlapping boundaries of villages in Nang Rong suggest intermarriage between different villages, perhaps as a way of reducing competition over land, a pattern later confirmed by the survey data. Further, the competition for land, evident in the manioc area to the west, results in less forested land available, and indeed this absence in some villages is associated with higher rates of outmigration of young men, who see a limited future due to scarcity of forested land for future farms.

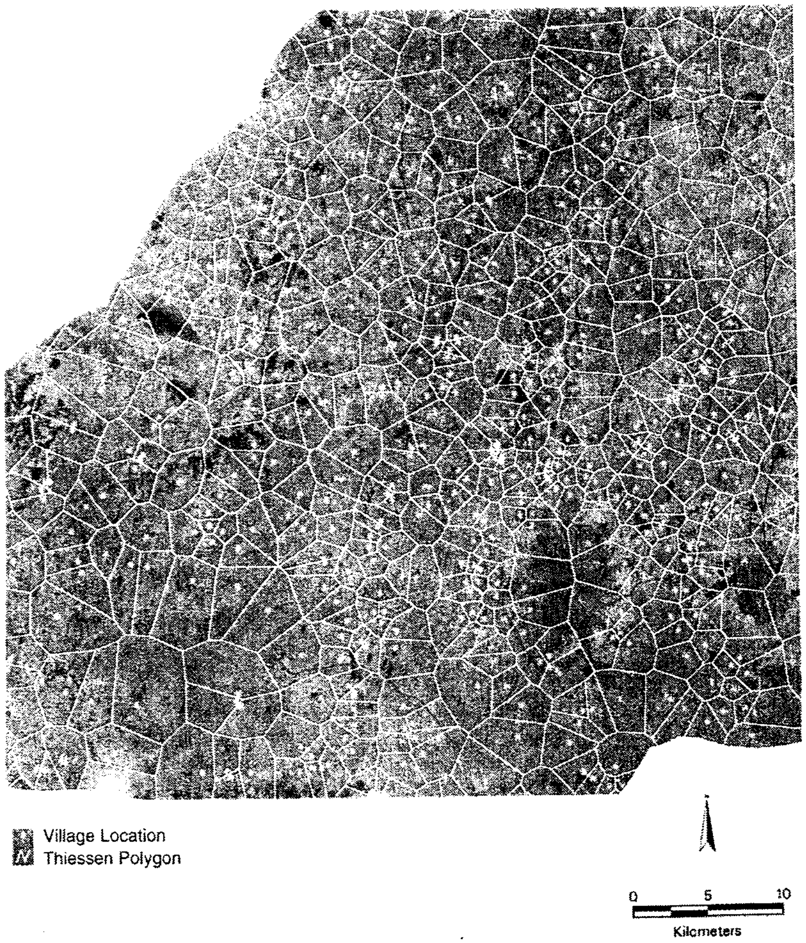

Figure 2.5. Raw Landsat TM (4, 3, 2) and Thiessen polygons, Nang Rong, Thailand, 1993.

Methods for Studying Rural Areas Where People Live on the Property

In contrast to the Nang Rong setting where human communities have populations that commute out to their nearby farm fields (see Figure 2.3B), there are also places throughout the world where people live not in villages but on rural farm properties, engaging in extractive, agricultural, and pastoral practices for both subsistence and market production. In this case, a majority of farm property households live upon the land that they use (see Figure 2.3A). Frequently these farm property households have

a nearly one-to-one relationship between the household and the farm property being used. An example of this type of situation would be our study area in Pará State, Brazil, to the immediate west of Altamira City and the Xingú River. This site has been studied from the early 1970s to the present (Moran 1975, 1976, 1981; Moran et al. 1994, 1996, 2000). Currently, there is a multi-disciplinary team of anthropologists, geographers, sociologists, and ecologists studying the relationship between farm property, household structure, health, and deforestation for a region of roughly 4,000 square kilometers. The area has a complex physiography ranging between 20 and 350 meters above sea level, with rolling hills in many areas and steep slopes in others. Farm property activities vary from cocoa and coffee production to manioc, and pasture used for cattle production.

This 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. 1994, 1996; Brondizio et al. 1994, 1996; Tucker et al. 1998). This study was undertaken to more fully understand land use and land cover change through the acquisition of aerial photography, Landsat Multispectral Scanner, and Thematic Mapper satellite imagery. GIS methods were incorporated in an effort to link classified remote sensing imagery and farm property household surveys in a spatially explicit manner. Along with the desire to link household survey data and land use/land cover information derived from classified images, GIS could be used to model other physiographic, geophysical, and biophysical characteristics of the region, along with human impacts on the landscape from the creation, extension, and improvement of road networks, other infrastructure, settlements, and urban centers. In the context of the Altamira study region, the combination of social science survey data, ecological field studies, remote sensing imagery, and the use of a GIS to bring these disparate data types together allows for a complex analysis and understanding of a diversity of variables that affect and in turn are affected by farm property, family structure, development processes, and deforestation in the region.

The research design for this project does, however, have significant differences from the research design described previously for the Nang Rong region. The initial design for the Altamira study concentrated on farm property land use/land cover and household family structure. This, on the one hand, could be seen as a constraint on our ability to scale down to the individual or to scale up to a community, but on the other hand, it allows for a more in-depth look at householders' strategies and the local decisions that have repercussions for a fairly large forest frontier region in the Amazon. Our focus on the farm household, and by extension the farm property, also allows for a more finely grained spatial-explicitness than that of Nang Rong, where spatial analysis for the past decade was only possible by aggregating individuals and households to a community or village level. This constraint is now being addressed by detailed parcel land research. In the Altamira site the initial development plan was designed to accommodate one family on one 100-hectare property. For Altamira, because our study is at the property level, we did not encounter the problems associated with the delineation of village/community boundaries that were encountered in Nang Rong. Therefore, it is also an easier task to link field-gathered ecological and social data with our land use/land cover image classifications in a GIS, without having to make decisions about how to infer household impacts upon an aggregated landscape.

In reality, however, linking farm households and properties with survey data and land use/land cover change classifications in a spatially explicit manner is not as straightforward as it might seem from the above description. A number of different steps were required to derive the property grid that we are currently using for analysis. For spatially explicit analysis of farm property household structure and land use/land cover change, it is necessary to have information or data that can be used to define a given property, its location, and its spatial extent. In the case of Altamira, it was necessary to build or acquire a property parcel map (i.e., the property grid) that could be used in the production and selection of our survey sample and then be linked with the survey data. Creating such a property grid GIS layer with unique identifiers provides a powerful tool for data extraction from the classified satellite imagery that we have developed. Exploratory analysis of these data permitted the development of a stratified sampling frame for selecting properties and households based on (1) timing of settlement from the period of initial forest clearing and (2) extent of deforestation. Other sampling criteria could be used with these data, based on the questions of interest and concerns with patterns of land cover and land use, or for identifying farm properties associated, for example, with particular soil types or topographic positions.

For purposes of generating a stratified sampling frame congruent with our research questions focusing on episodes of deforestation, a property-level analysis seemed very useful. Explicit in our model is the need to disentangle *period effects* (e.g., credit policies for cattle and cocoa) from *cohort* (e.g., groups of immigrants) and *age effects* (e.g., length of time of a household on the farm) 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 were able to compare households at similar stages of farm development and stages of the household life cycle for different periods.

There are a number of different ways in which one can produce or acquire a property grid. Development of the property grid overlay proceeded by deriving 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) tablet digitizing of roads, (2) on-screen property definition and digitizing, and (3) property identifier assignment. The technique outlined here may not 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 (see Figure 2.6). The farm lots average 100 hectares in size (500 m by 2,000 m) and are, therefore, represented by approximately 1,100 pixels (per lot) in a TM image where pixels are generally 30 by 30 meters. 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. Distinguishing property boundaries facing the road often required only a quick visual analysis. However, determining the interior or back border of properties in this grid scheme was not always so straightforward and required interpolation of a medium distance between the two properties

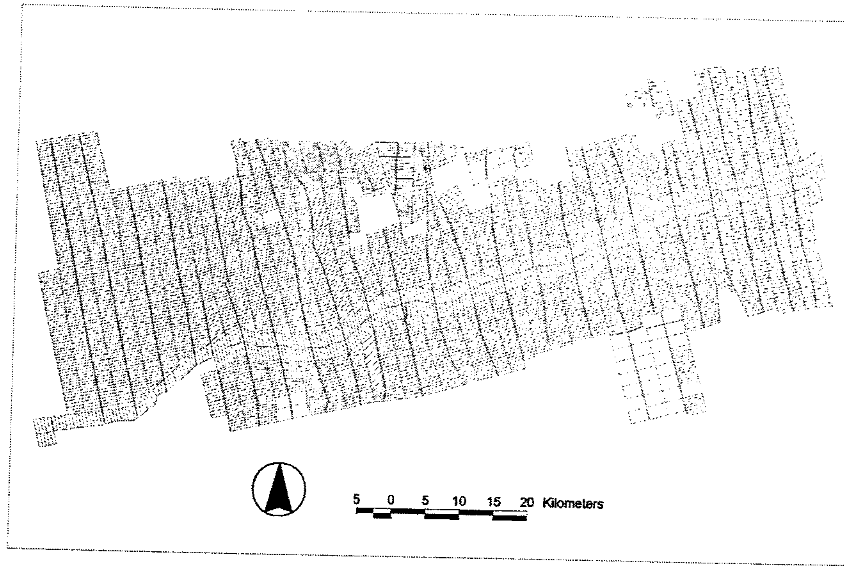

Figure 2.6. The Altamira property grid.

that shared back ends. This method proved useful and adequate for initial analyses but contained spatial error as a result of the uncertainty in the location and extent of the real property boundary, especially for the back end of the property parcels that are commonly covered in 100 percent forest canopy and thus cannot be discriminated by the TM sensor. This approach would also prove problematic as property settlement extended further into the forest frontier where properties were less developed and a majority of properties were still close to 100 percent forested. The other concern with continuing to use this technique is the large number of properties (over 4000) that were planned for this settlement project. This work also took advantage of data gathered in the field, where 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 field team used a Trimble Pathfinder system and also had a Magellan, ten-channel differentially capable, pair of units as a backup system. The 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 the development of a stratified sampling frame, helped the interview teams locate households and farms for interviews. In the field, laminated composites of bands 5–4–3 of the 1985, 1988, and 1991 TM images and aerial photographs from 1970 and 1978 were carried to discuss land use and land cover with farm families. GPS points were also collected at the houses interviewed and, during discussion with farmers, their properties were identified. This identification process assisted in the evaluation of the property boundary, as well as the investigation of the quality of our remotely sensed land-cover classification. In many cases it was possible to show farmers single-page printouts of the composite and classified land-cover class images for the above dates for their farm and adjoining properties. The data gathered in this way were particularly useful in verifying 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, more recent property maps were obtained from the colonization agency, or Instituto Nacional de Colonização e Reforma Agraria (INCRA). These maps were developed over different periods for different sections of the Transamazon highway feeder roads and were pieced together to cover the entire area covered by our study region. These maps were produced at a 1:50,000 scale, using the Universal Transverse Mercator coordinate system, and although pieced together, appeared to be much more accurate survey maps of the region. There are two different approaches, each containing multiple steps that can be taken to transform a paper map into a spatial data set. One way is to use a digitizing tablet or table. The other is to use a scanner. When using a digitizing tablet, the source map is converted directly into a vector data format. One positive aspect of using a digitizing table for conversion of a paper map into a GIS dataset is that it is possible to acquire digitizing tables that can fit even the largest map sheets. A few drawbacks of digitizing tables and tablets include the technical difficulties related to software driver support and communication between the digitizer and the GIS or CAD software being used and the possibility of moving the map on the digitizer between digitizing sessions. With big digitizing projects (which can take weeks or months to complete), changes in environmental conditions can stretch and shrink the paper map being digitized. Digitizers also have limited resolution; though with very good ones resolution should not be a substantial issue.

The other approach that can be used to transform a paper map into a spatial data set is to scan the map and digitize it on-screen (sometimes referred to as on-the-fly or heads-up digitizing), but there are a few disadvantages to this method. Large maps are often difficult to properly scan, even when one has access to a large-format drum scanner. The raster image files that are produced can be very large and require large amounts of storage space and a large amount of memory to process. The necessity for large amounts of digital storage, ranging from less than a gigabyte up to terabytes in size, and the requirement of large amounts of RAM (random access memory) to manipulate raster data have in the past posed difficulties, both from a financial perspective and in terms of raw processing time necessary to accomplish given tasks. However, computer equipment continues to improve in quality and raw power, and the scanning and manipulation of large images is becoming an increasingly efficient and cost-effective method for transforming older non-digital map libraries into digital data that can be stored in and manipulated by GISs. Besides the decreasing physical and financial constraints, the scanning of maps for use in creating spatial data sets does still entail other problems, though generally different than those difficulties associated with digitizers. Scanning a map in pieces can lead to difficulties in properly merging and aligning images, particularly edges. Scanners themselves can also distort the images produced from the scan if the scanner is not properly calibrated. Scanning also has advantageous qualities. When a map is scanned, it is converted from its paper form to a digital raster graphic or image file. This image file can then be manipulated in various ways to automate the extraction of the data contained in the map, and the transformation and projection of the image to its coordinate system can be applied to the raster data set before any vector attributes are extracted.

For production of the new property grid based on the newly obtained maps, the latter method was chosen. Sections of the 1:50,000 scale property grid sheets were scanned. These scans were saved as digital images that were then registered, transformed, and projected to the appropriate coordinate system using both GPS points collected in the field and 1:100,000 scale topographic sheets as a reference. These were merged together and used as a raster base in a GIS, where the properties were then hand digitized. 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.

A comparison of the pre-field and "new" property grid indicated that the digitizing of property boundaries from satellite images worked relatively well, but that there were a few errors along some roads. We also had the additional problem of property islands being created by detours in the roads. In some instances, farmers left these pieces of land idle. Others allowed neighboring farmers to use them or property boundaries were re-negotiated. These changes were not surprising, given the gap between 1991 and 1998 fieldwork and the probability that farmers adjust roads to meet their transportation needs and in response to local soil, hydrological, and topographic patterns. However, with further analysis, errors of mis-registration were identified. These errors were perceived initially to be errors in the production of the property grid from its source. However, upon further exploration, we found that not to be the case, but rather that the scans for the mid-section were mis-registered north to south by one property. This mis-registration in the center of the property grid caused distortions in the whole property grid, requiring realignment of individual sections. Though we had found this one striking error in our initial production of the property grid, we did continue to have other problems that had two different sources. One of these problems was the initial property grid. The further the properties were from the Transamazon highway, the less reliable they appeared to be, and the layout of the roads that the properties were aligned along changed over time as the constraints imposed by nature altered the usable road network and property grid from the ideal evenly spaced grid that had been planned. The second problem was related to the scale of the original property grid and our desire to match properties with image classifications using 30-meter pixels. It was necessary to check the boundaries of the properties created with the property grid with our classified image data. In most cases the properties were within a pixel or two of where our visual inspections, combined with our intimate knowledge of the study area and the drawings and notes collected in the field for the properties that were surveyed, believed they should be. It was therefore necessary for us to move the boundaries of the properties one or two pixels in a given direction. It became obvious that engaging in such a process for all of the properties of the study area would be difficult and timeconsuming (being based on intuitive and experiential shifts in the data, rather than on a quantitative or mathematical transformation), so the decision was made to concentrate on aligning the properties that we had surveyed as closely as we could.

Work on a new property grid, independent of the pre-fieldwork grid, has been completed for the area of colonization from 20 to 120 kilometers west of Altamira. Example subsets of the original property grid and the derived spatial data are provided (Figure 2.7), along with a map of the overall property grid overlaid onto a 1996 Landsat TM Image (Figure 2.8) of the total study region.

The example subsets illustrate clearly the differences between the original map product (once scanned) and the derived property grid. The property grid produced has already been used to extract farm property and household data for a number of research publications (Moran et al. in press; Brondizio et al. in press).

Additionally, we have also converted the data from the IBGE 1:100,000 scale topographical sheets into digital format. The spatial data derived from these maps includes topography, hydrography, and roads. The topographic (contours and spot elevations) and hydrographic data provide the necessary data for the creation of detailed digital terrain models (DTM). These models can either be vector based as in triangulated irregular networks (TINs) or raster based in the form of a digital elevation model (DEM). Both DTM types can be used to create additional secondary data sets, including slope, aspect, curvature, and others, for the landscape. In combination with the classified imagery, the farm property household data, and the ecological field training sample data gathered in the field, we have a complex combination of spatially and temporally explicit data for analysis.

Conclusions: What Have We Learned About Inferring Household Behavior in a Spatially Explicit Landscape?

In this chapter we began with a review of current approaches and issues for examining household behavior in a number of different spatially explicit landscapes including urban areas, rural areas where people live in villages and commute to their landholdings, and rural areas where people reside on the land they use. For each of these spatially explicit settings, we presented distinct challenges for the linking of households to land cover change, and for inferring the behavior of households, using remotely sensed data within a geographic information system (GIS). Each of these three area types has distinct challenges and problems associated with the analysis of household impact upon the landscape. In the urban setting, inferring the behavior of households on the landscape is currently a very difficult prospect, as a result of either the density of the population (and therefore housing) or a lack of data taken at a fine enough spatial resolution. This limitation is being overcome with the arrival of extremely fine-resolution satellites. This is less of a problem when an urban family owns a farm property. In this case it is possible to analyze the impact of that family upon the farm property with remote sensing and GIS data, but still difficult to do so for the urban property (unless the household is wealthy and the property in the city is a large estate). In the urban setting it is also difficult to adequately separate household impacts on the surrounding landscape, because households influence land that they do not own in aggregate with other households in the surrounding neighborhood and throughout the overall urban landscape. In the case of villages or settlements where households live and commute out to their farm properties, it is difficult to fully disentangle the household from the community properties, and it is difficult to fully disentangle the household from the community, but village-level inferences can be made about marriage patterns, land ownership, and likely migration patterns. This is why the Nang Rong study chose to aggregate households to the village level. For the Altamira site, where most of the households and farm properties are synonymous, the problem of disentangling the household from the community is less difficult, though as time passes this will become more difficult, as properties are consolidated, single households acquire multiple unattached properties, farm properties become subdivided, and households move to the city while continuing to manage their farm properties. For example, we can see, by the geometry of land clearing, where land consolidation is taking place, whether it is driven by pasture formation or intensive cropping, and infer the social dynamics of land cover change at the level of the individual property. In this work we have linked demographic, social survey research to finely detailed time-series of Landsat TM, MSS, and aerial photography to construct a temporally and spatially fine-grained analysis of changes in land cover at both the landscape and individual property, so as to achieve accurate inferences about the behavior of households. We have been able to infer that land consolidation is preferentially taking place close to town and on poorer soils—subsequently confirmed by survey data.

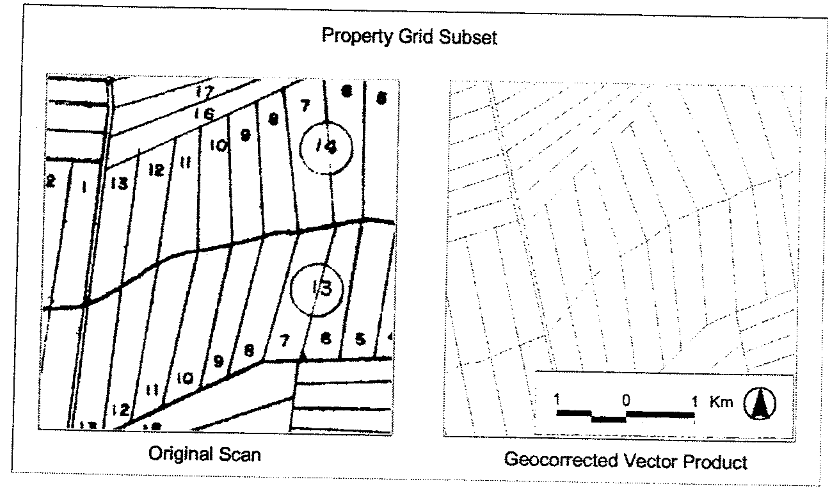

Figure 2.7. Example of property grid—original scan and derived product.

Integration of social and spatial data provides an effective mechanism to explore the inter-relationship between human behavior and landscape change. A number of spatial operations allow spatial and social data to be integrated. Collectively, these methods are referred to as data transformations. For example, population data collected at the community level (point data) can be interpolated to provide a continuous surface of

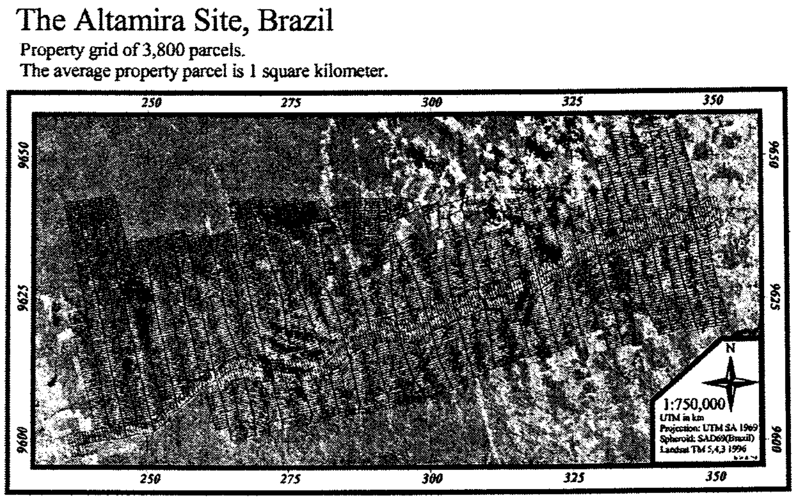

Figure 2.8. The Altamira study region with property grid overlay (TM bands 5-red, 4-green, 3-blue, converted to grayscale for publication). See color version at http://www.csiss.org/best-practices/siss/02

population density. Such a population density, or distribution, surface can be overlaid with a landcover change map to find a correlation between high population density and areas where deforestation is occurring. However, one must be careful, since interpolated surfaces do not always represent adequately the true distribution of phenomena, nor are some variables amenable to interpolation (e.g., nominal data such as ethnicity and occupation). A one-to-one-to-many linkage can also be made between social units of observation (e.g., households) and the landscape associated with that spatial unit. A one-to-one linkage associates the social unit to a single partition of the landscape, such as a household, which resides on a single land parcel (as in the case of Thailand discussed in this chapter). A one-to-many linkage associates the social unit of observation to multiple partitions of the landscape, as when a household is associated with multiple landholdings scattered across the landscape (as is often the case with minifundios or micro-parcels). Inferring the behavior of households from spatial data needs to take into account the varying definitions of communities. In the case of Nang Rong, Thailand, the administrative definition of a village differed from the spatial and the social definitions—and over time, the political definition administratively partitioned a social village into multiple political villages. This is not an unsolvable problem, but it does require adequate ground truthing of what constitutes the units of observation of socially and politically driven spatial divisions (Evans and Moran 2002).

The three examples provided in this chapter present distinct challenges to inferring the behavior of households from the use of spatial data, using remotely sensed information such as Landsat TM. Certainly, the ability to link a particular household to a particular landscape partition is a powerful tool for understanding human behavior

over time and space. The pattern of land settlement plays a key determining role in the procedures likely to work in making such inferences. Private land parcels associated with distinct households provide the opportunity to create distinct partitions in the landscape and to link the behavior of households to landscape changes within that property space. When this one-to-one association is not present, spatial data transformations can be used to understand community-level behavior within a larger landscape unit, and even larger regional units.

The discussion that we have provided here has led to a number of conclusions about conducting research into the spatially explicit behavior of households using remotely sensed imagery, household surveys, and GIS techniques. It is clear that it is possible to link rural households in some contexts to spatially fine-grained LULC classifications, but that it is costly in that it requires many skilled, knowledgeable, and motivated research team members. Such research also requires extensive use of GPS equipment, GIS and remotely sensed image laboratory work, and extensive fieldwork, which all require time and adequate financial resources. In many situations, especially in the developing world and less developed frontier regions such as in the Amazon, property maps and property boundary data will be spatially imprecise. This will change over time, as more cities and roads develop in these regions, along with the infrastructure to maintain them. This is often accompanied by increased surveying and more accurate and up-to-date creation of spatial data. The increasing availability of fine-grained satellite imagery, such as IKONOS and Quickbird (previously mentioned), may accelerate this process but this will only be seen in time. The most important component to all of this is that, for spatial analysis, positional accuracy is of the utmost importance, along with methods that provide data that are finely grained enough for household-level analysis and for precise spatial modeling.

This type of study requires a multi-faceted team of researchers with a great diversity of skills. It is unlikely that one person would be expected to master all of the individual skills necessary to conduct this type of research. There needs to be a small core of researchers who can develop and refine the questions to be asked and the theories to be addressed. It is then necessary to have individuals who can work in the laboratory as well as in the field. In order to engage in spatially explicit analysis of households, it is necessary to have spatial data that clearly define the household unit (or possibly even the individual) in a meaningful and analytical manner. This means that to do such research it is necessary to have spatial data that represents explicitly the location and extent of household property holdings. These data also need to be available at a scale that is reasonable in relation to the average, minimum, and maximum sizes of the properties in question. This type of analysis is difficult when households own multiple dispersed properties of varying sizes. Another significant problem is that analyses of this type are often the result of interest in dynamics in frontiers or economically less developed regions. These regions frequently have poorly developed spatial data sets, and even if they have reasonable maps, those maps are not very likely to be available in a digital format. The best practice for engaging in spatially explicit analysis of household scale dynamics is for a very large team to first go to the location and hand survey the extent of all properties in the region of interest. However, this is unlikely to occur, as it would be prohibitively expensive and labor-intensive. Despite this expense, it may be productive for researchers engaged in similar projects to engage in partnerships and data sharing that encourage the exchange of higher quality spatial data and maintain ties with local planning agencies in order to achieve a high degree of contextual awareness.

Notes

1. The USGS/Anderson Classification system was designed to provide a systematic hierarchy of land cover and land use characteristics for use in the classification of satellite remote sensing imagery. The system has a number of different levels that are hierarchically organized and become increasingly complex. The first level in this system includes: urban or built-up land, agricultural land, rangeland, forest land, water, wetland, barren land, tundra, and perennial snow or ice (Anderson et al. 1976). Most remote sensing imagery acquired from satellites is suitable for Level 1 to Level 2 classification. Improvements in remote sensing technology are quickly improving the possibility for classification of the landscape to four hierarchical levels within this system of classification. It should be noted that this is only one classification system, and that its popularity is driven partially by its adoption by the USGS. Many other classification systems are possible, but they frequently have substantial similarity to this system.
2. Space Imaging Inc. IKONOS, launched in 1999, and Digital Globe's Quickbird, launched in 2001, provide commercial satellite imagery products available to the general public and the research community that is on par with or slightly coarser than aerial photography and that has much higher spatial resolution than previously available imagery, such as Landsat MSS (79 m), Landsat TM (30 m), Landsat Enhanced Thematic Mapper Plus (ETM+) (30 m multispectral, 15m panchromatic), or SPOT (20 m multispectral, 10 meter panchromatic) imagery. Both the IKONOS and Quickbird sensor provide panchromatic and multispectral image products. IKONOS panchromatic has an optimal spatial resolution of 1 meter, with a spectral range of 450 to 900 nm. IKONOS multispectral imagery has an optimal resolution of 4 meters in four bands: (1) blue, 450 to 520 nm; (2) green, 520 to 600 nm; (3) red, 630 to 690 nm; (4) near-infrared, 760 to 900 nm. Quickbird panchromatic has an optimal spatial resolution of 61 cm, with a spectral range of 450 to 900 nm. Quickbird multispectral imagery has an optimal resolution of 2.44 meters in four bands: (1) blue, 450 to 520 nm; (2) green, 520 to 600 nm; (3) red, 630 to 690 nm; (4) near-infrared, 760 to 900 nm. The spectral range is identical between these two image products and similar to TM and ETM+ satellite image sensors. For product and image sensor specifications see: (1) http://www.spaceimaging.com, and (2) http://www.digitalglobe.com.

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