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Land-Use Change After Deforestation in Amazonia

Emilio F. Moran and Eduardo Brondizio

This chapter describes a project that linked traditional social science and biological field methods with remotely sensed data to further understanding of how human decisions about land use have influenced both rates of deforestation and subsequent secondary successional rates of regrowth in Amazonia. The impetus for this project was a workshop held in 1987 that introduced ecological anthropologists to remotely sensed data as a tool in addressing substantive social science questions at a regional scale. The workshop emphasized the importance of developing a partnership between social scientists and colleagues having sufficient expertise in remote sensing to solve the complex technical problems likely to be faced, and it did so without failing to note that this partnership would be best served if the social scientists developed a minimum level of proficiency in remote sensing to facilitate joint research and analysis.

Much of the promise of the new remote sensing techniques comes from expanding the areal extent of studies so that regional-scale phenomena such as land-use change can be addressed. The very advantages of small-scale studies (intimacy with informants, richness of the social network, insights into household structure) limit the ability of investigators to examine larger-scale phenomena. Remote sensing's larger spatial capabilities expand the kinds of questions that can be studied.

The published work on Amazonia in the 1970s and early 1980s spoke of devastating deforestation, desertification in the humid tropics, and wholesale conversion of tropical forest to pasture; it also made incorrect assumptions, such as 100 percent combustion of forest biomass (Lean and Warrilow, 1989; Booth, 1989). These themes, commonly expressed in studies based on remotely sensed

data, did not ring true to those who formulated the project documented in this chapter. Past social science research in the area had noted farmers' complaints about the difficulties they faced from rapid regrowth of the vegetation cover following cutting and burning of forest (Moran, 1976, 1981). Secondary succession rapidly covered exposed ground and resulted in substantial land cover. Yet the large-scale work using remotely sensed data hardly mentioned secondary successional vegetation and rarely if ever suggested the significance of this vegetation to processes such as carbon sequestration, biodiversity, and land-cover dynamics.[1]

The result of these reflections was the decision to craft a set of proposals based on the same technology as that used by the remote sensing community—Landsat Thematic Mapper (TM) digital data—to understand land-use/land-cover change dynamics following deforestation, particularly the factors that might explain the differential rates of secondary succession. A grant provided by the National Science Foundation's (NSF) Cultural Anthropology Program enabled one of the authors (Moran) to become familiar with the theory and techniques of remote sensing. In fact, the Senior Scholar's Methodological Training Grant program[2] has provided support for several environmentally oriented anthropologists to acquire technical skills in other disciplines and has substantially increased the number of scholars engaging in this type of work. The following chapter by Entwistle et al. is an example of another means of linking remote sensing and social science. Following this 1-year learning period, grant support from the NSF Geography and Regional Science and Human Dimensions of Global Change programs made it possible to apply these newly acquired skills to the questions raised above.

The second author of this chapter (Brondizio), who had acquired some of these skills at Brazil's National Institute for Space Research (INPE), followed a reverse trajectory. He had familiarity with agronomy, vegetation ecology, land-use studies, and remote sensing research and undertook to learn social science methods, especially ethnographic skills, while pursuing a Ph.D. in environmental sciences.[3]

A common research question meaningful to the social and environmental sciences—what forms of land use lead to given rates of secondary successional regrowth in Amazonia—provided the epistemological basis for our collaboration. The choice of soil by a homesteader, the choice of area to be cleared, the method used for clearing, the timing of burning, the choice and sequence of crops planted, and the frequency of weeding all affect the rate at which pioneer species can colonize an area of land, the composition of that succession, and the differential survival of mature forest species. The study of secondary succession requires integration of conventional site-specific research methods in vegetation ecology and ethnographic data with more inclusive scales through remote sensing analysis of land-use and land-cover patterns (Moran et al., 1994; Brondizio et al., 1996).

This chapter presents examples from our work that illustrate the linking of remote sensing and human ecological questions in understanding land-use and land-cover change in Amazonia. The chapter does not describe specific methodology and technical details related to image processing, spectral analysis, and vegetation/soil inventory techniques, for which readers are referred to published papers written by the authors and their collaborators (Mausel et al., 1993; Moran et al., 1994; Brondizio et al., 1994, 1996; Li et al., 1994). As with other chapters in this volume, the objective here is to discuss how collaboration between the social scientist and the remote sensing expert developed, summarize the findings and insights gained by linking remotely sensed data to traditional social science field research, and explore ways of advancing this type of collaborative work in the future (e.g., Mausel et al., 1993; Moran et al., 1994, 1996; Brondizio et al., 1994, 1996; Li et al., 1994; Brondizio, 1996; Randolph et al., 1996; Tucker, 1996; Tucker et al., in press). The work discussed here brought together remote sensing, botany, environmental sciences, soil sciences, anthropology, and geography. It did so incrementally, as interest grew in the issues raised by our research among collaborators in Brazil and the United States. In other words, building on a core set of questions and the expertise of anthropology, ecology, and remote sensing, the project has expanded to address other concerns that flowed naturally from the original set of propositions. This expansion was anticipated and was integrated without difficulty. Even now, the project anticipates incorporating climatologists, zoologists, demographers, economists, and conservation biologists.

THE VALUE ADDED OF SOCIAL SCIENTISTS' INTEREST IN REMOTE SENSING ANALYSIS

Social scientists bring to the analysis of global change and its remote observation a concern about and an expertise in the behavior of people at the community and household levels and a desire to understand the human face behind the pixels (see Geoghegan et al., in this volume). When looking at a satellite image, for instance, social scientists are inclined to search for land-use patterns associated with distinctive socioeconomic and cultural differences. Consequently, they search for driving forces behind land-use differences and for land-cover classes that represent culturally and biologically meaningful differences, in contrast to, say, naming classes after a standard vegetation class. For example, the timing of credit availability for pasture or cocoa development can help determine when one might begin to see the appearance of these classes with higher frequency on a landscape, or the creation of a class called "roça," which is a mixed subsistence garden dominated by manioc and bananas. This poses a challenge in that if a culturally meaningful category is present (e.g., palm agroforestry) and is associated with important behavioral differences (i.e., particular steps in preparing these orchards through time until they reach the desired density), then an effort must be made to sample enough cases so that the phenomenon can be distinguished spectrally and classified (Brondizio et al., 1994). This may not always be possible, but it is a challenge that social scientists, or at least anthropologists, are likely to bring to the task of field work and land-cover classification. On the other hand, while a culturally meaningful category may exist, it may be so rare that one cannot possibly obtain enough observations to separate it spectrally, or it may not be different from other culturally differentiated classes that are spectrally alike. It is still a challenge, for example, to differentiate between many types of agroforestry and other mixed-crop systems given the current resolution of satellite images. Some of these problems may persist until such time as orbital satellites with a resolution of 1 m are available to researchers. The first satellites with this resolution are expected to be launched in the next year or two and, because they are launched by commercial enterprises, are expected to make data available more promptly than is the usual current practice and to customize the data to the needs of users.

Without a social scientist as part of the team, culturally important dimensions of land cover may quite possibly be overlooked by scientists who bring a nonlocal or purely remote point of view to the analysis of the data. The best example from our work is the discrimination of managed (palm agroforestry) from unmanaged floodplain forest in the Amazon estuary (Brondizio et al., 1996). Whereas these are vegetation classes with extremely similar structural characteristics and thus are commonly mapped together, managed floodplain forest has local economic significance that requires attention when one is studying an estuarine population at a regional scale. By combining traditional ethnoecological field techniques that elicited culturally meaningful categories (Açaisal) with spatial distribution considerations elicited by the satellite data, it has been possible to distinguish between these two culturally and economically distinct vegetations (i.e., managed and unmanaged floodplain forest). When the importance value[4] of the palm *Euterpe oleracea* reached 0.6, it became possible to distinguish spectrally a managed açaí palm agroforestry grove from the adjacent floodplain forest from which it had been developed by local farmers (Brondizio et al., 1994:261).

While there is no substitute for the use of traditional ethnoecological field data collection to obtain a deep understanding of native knowledge of the environment, it is possible in cases such as that described above to collect a sufficient number of observations to create spectrally differentiable classes of land cover from native categories—although success in this enterprise will rarely economize on data collection costs. What will be gained, as in most applications of remote sensing, is the ability to map at a regional scale the distribution of a land-cover class that is meaningful to a local community over a much larger landscape than is otherwise possible (Brondizio et al., 1996). The value of forecasting cereal harvests and yields of major commodities has been accepted for years in agribusiness. There is no reason, other than the more modest resources of the scientific community, why forecasting of harvests of locally valuable crops, such as manioc, bananas, or agroforestry groves marked by a dominant, cannot be undertaken. One of the important results of the study of palm agroforestry has been to show in dramatic fashion the very large areal extent of this economic activity, its economic value to the regional economy, and the achievement of this outcome with minimal loss of forest (a five-fold rise in economic value at less than a 2 percent loss of forest cover).

Even with current limitations on spatial resolution that can mask households' complex patterns of land use, anthropological and geographical understanding of the spatial distribution of sizes and locations of agricultural fields makes it possible to infer and interpret land-cover patterns that are distinguishable spectrally. This ability has been enhanced with the growing use and accuracy of technology that permits accurate location, such as Global Positioning System (GPS) devices.[5] However, the difficulties of distinguishing among coffee plantations, early secondary succession, and degraded pastures should not be taken lightly. Few analysts have tried, and even fewer have succeeded, to differentiate spectrally among types of crops, types of pastures, and types of agroforestry. The more homogenous a stand is, the more likely it is to be identified consistently with a high degree of accuracy, whereas for mixed and heterogeneous vegetation formations, such accuracy is difficult to obtain. Our own work has been able to differentiate among three distinct structural classes of secondary succession with an accuracy of 92 percent, and between managed and unmanaged floodplain forest with an accuracy of 81 percent (Mausel et al., 1993; Brondizio et al., 1996). These successes do not suggest that achieving these results was easy. On the contrary, many classes we wish to differentiate have remained elusive. Monitoring oil palm and cocoa, for example, has to date proven impossible given the very large spectral differences among their various developmental stages. We believe it should be possible to do so if sufficient resources are devoted to collecting enough observations for the distinct steps in the development of these plantations—a goal very different from ours of understanding secondary successional processes.

An excellent example of the application of remote sensing to fundamental issues in social science is a study by Behrens et al. (1994) that shows how settlement history mediates the effect of population pressure on indigenous land se. Sendentism and the market opportunities that promote it seem more important drivers of land-use intensification and tropical deforestation among contemorary native Amazonians than population growth itself. Village formation and attle ranching are associated with greater landscape heterogeneity, but fewer oody species. Concentrating in large villages a population that has been distribted areally over the landscape can intensify deforestation, particularly when xacerbated by the development of pastures and irrigated rice cropping. The udy of intensification is of fundamental interest to the understanding of human cieties through time, and remote sensing is an excellent tool for observing the tent and intensity of its impact.

One of the most important contributions social scientists can make to this e of research is to help construct data collection protocols that capture the es of socioeconomic data most closely related to land-use dynamics. It is all common for those outside the social sciences to try to explain land-cover

change in terms of population growth, rather than applying the more nuanced approach needed to understand the relationship between population (growth, distribution, structure) and the environment. A current project of the authors involves investigating, at the level of the farm property, the role played by the demographic structure of each household in changing uses of the land, with a view to predicting rates of deforestation from a knowledge of household composition. There is a need to develop a protocol for the minimal data needed to support ecological and remote sensing analysis and also be meaningful to the social sciences. For example, such a protocol might include data related to production systems (types of economic importance), a calendar of activities throughout the year (land clearing, planting, weeding, harvesting, fallowing), soil and vegetation management techniques, the demographic composition of households and populations, time allocation in different production systems, land-tenure structure, and an ethnoecological classification of ecosystem components (Moran, 1993; Brondizio, 1996). For example, one should expect significant differences in the way land cover develops and changes through time as a product of, say, private or communally held forest. Current studies by our research group in seven Latin American countries are aimed at elucidating the impact of tenure and other social organizational arrangements on the composition and longevity of forest cover through time.

METHODS

Levels of Analysis and Site Selection

From the outset, we have followed a systematic approach to site selection and comparison. Taking a contrary view to that commonly held, we hypothesized that the differential rate of secondary succession would most likely be influenced by initial soil fertility, the history of land use of a deforested area, and the spatial pattern of land-use and land-cover classes. Soil fertility had seldom been related to or soil data collected in studies of forest ecology and succession (Buschbacher et al., 1988). Since tracking of age classes of secondary succession and biomass accumulation in such vegetation had not been performed in Amazonia using Landsat TM (and had been unsuccessful using the Multispectral Scanner [MSS]), we began our study by examining two locations. Each was characterized as having relatively fertile soils, so that if it were technically possible to differentiate stages of secondary succession, the change might be measurable in the relatively brief time span between 1984 and 1991 during which TM was available. For the sake of contrast in both environmental and land-use terms, we selected an upland site that was well known to one of us from earlier work (Moran, 1976, 1981) and an estuary area where we had done preliminary work (Murrieta et al., 1989). Following 2 years of research at these two sites, we worked at three other Amazonian sites, characterized by relatively nutrient-poor soil conditions and different patterns of land use.

One of our goals from the outset was to link detailed ethnographic data, species- and stand-level data, and land-use histories to the spectral analysis so that we could achieve not only a field-level understanding of changes in land cover, but also a regional analysis of land-use and land-cover change. Doing so required that we work with a large portion of the TM scene, and that our sampling design be distributed over the image in order to incorporate spatially variable phenomena, such as different kinds of settlements, different land-tenure arrangements, different types of vegetation, and different soil types. Thus, we sought to link the behavior of households in farms and settlements to regional-scale processes of land-cover change, especially secondary succession. We also wished to link these results to global carbon models and Amazon Basin models—a task that has been pursued more directly by Skole and his collaborators (e.g., Skole and Tucker, 1993).

Figure 5-1 illustrates the multiscale and multitemporal approach pursued in our studies. Our analysis begins by selecting locations that fit our fertility gradient design and have representative patterns of land use and population distribution. We also take into account data availability and the presence of colleagues with whom joint work might be undertaken that would enrich local institutions with both data and expertise. For the selected locations, we seek available cloud-free images of the study areas; depending on availability, we also try to obtain a set of images providing data intervals within which the processes of change can be observed, at least one of which is coincident with our field research. These data are then georeferenced and registered, exploratory spectral analysis is carried out in small subsets representative of different patterns of land cover, and this analysis is then used to carry out unsupervised classification of land cover over the entire study area. Details of our technical procedures have appeared in a number of publications (Mausel et al., 1993; Moran et al., 1994; Brondizio et al., 1994, 1996; Li et al., 1994).

We then proceed to the field, not merely to carry out field observations of land cover—the most common method of ground truthing—but also to interview at length land users who are identified from the initial analysis as having land-cover classes of interest for sampling and are distributed over the entire image. All of these visits to farms generate valuable information. Some are not entirely successful, either because the land has undergone transformation since the TM scene was taken or because there is error in the unsupervised classification. Detailed household surveys, with particular emphasis on the history of land use, are then undertaken. Following these surveys and a visit to the forest or secondary successional area, we request permission for the larger team to come to the property to carry out a detailed soil and vegetation inventory.

The resulting data are entered into a spreadsheet in the field, and adjustments are made in the sampling to ensure that a representative number of classes of

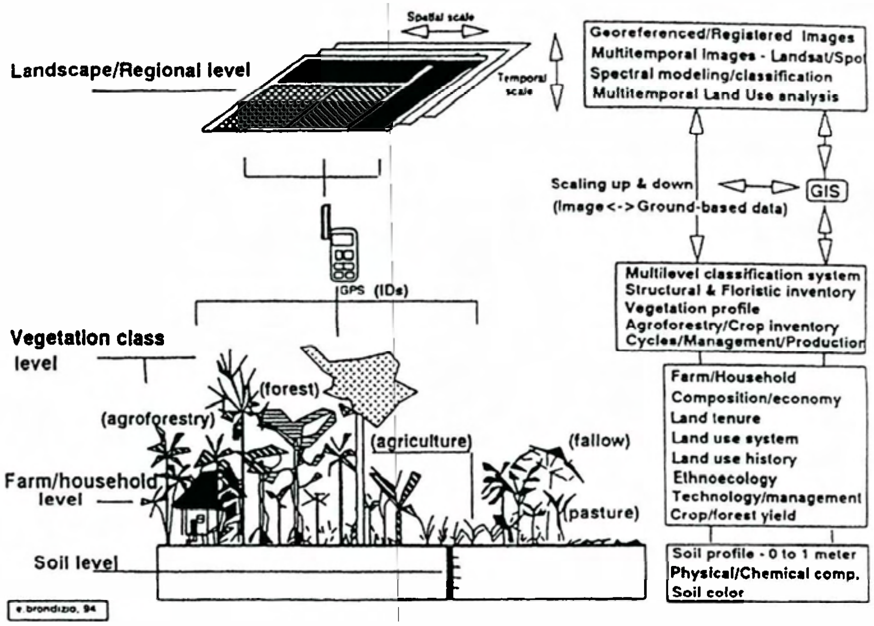

FIGURE 5-1 Methods of multilevel analysis of land-use and land-cover change.

vegetation are sampled. Each area at which soils and vegetation are sampled is georeferenced with a GPS device, every effort being made to choose study areas large enough so we can be sure of their location on the printouts of the TM scene we have prepared in advance and laminated for field use. These image printouts are generally prepared at a scale of 1:30,000 with a 1 × 1 km grid of Universal Transverse Mercator coordinates that allows us to locate each site (through use of GPS) while in the field. Fields as small as 1 hectare (ha) are clearly visible in these image maps, although we commonly select larger areas within which to take vegetation and soil samples. The use of these image printouts prepared at a fine scale and enhanced for visual interpretation has proven particularly valuable in extracting field information. The relative ease of understanding color composites (TM bands 5, 4, 3)[6] makes it possible to discuss land-use and land-cover features with local farmers with a minimum amount of explanation. Their discussion of the image provides an invaluable source of information about land-use and land-cover dynamics and makes sense out of the distribution of the different types of land cover encountered. In addition to the field-sampled plots, one or more members of the team collect "training samples" (i.e., visual observation of hundreds of locations) in order to obtain a robust supervised classification of land-cover classes upon returning from the field.[7]

Upon returning from the field, we use the GPS-referenced field observations to develop the supervised classification. We also perform accuracy analysis to determine the extent to which classification accuracy of at least 85 percent have been achieved. A second season of field work has characterized our work so far, at which time we are commonly able to double our field inventory data and refine the accuracy of the land-cover classes.

During the past 5 years our group has developed an extensive data set. This data set is focused on secondary succession and land-use and land-cover change in five Amazonian regions distributed along a soil fertility gradient representing relatively nutrient-rich (eutrophic) to relatively nutrient-poor (oligotrophic) conditions.

Study Areas

Altamira, in the Xingu Basin, is characterized by patches of nutrient-rich soils (alfisols) and less fertile soils (ultisols). Ponta de Pedras, in Marajó Island, is characterized as a transitional environment composed of upland nutrient-poor oxisols and flood plain alluvial soils. Igarapé-Açú, in the Bragantina region, is a mosaic of oxisols and ultisols. The soils of Tomé-Açu are dominated by oxisols and ultisols, both acidic and low in nutrients. They are less sandy in textural characteristics than those in Bragantina (Igarapé-Açu) but more so than those in Altamira or Marajó. Finally, Yapú, located on the Vaupés (a tributary of the Rio Negro), is composed of large patches of extremely nutrient-poor spodosols intermixed with stretches of oxisols.

Land use varies among these areas. Altamira, which lies along the Transamazon highway, began being colonized in 1971 and has experienced high rates of deforestation and secondary succession associated with the implementation of agropastoral projects. In contrast, Marajó has historically been home to native nonindigenous (i.e., Caboclo) populations occupied primarily in agroforestry activities in the floodplain and swidden agriculture in the uplands, along with some recent creation of pastures and mechanized agricultural fields. Land use in the Bragantina region has gone through several phases; today short-fallow swidden cultivation is dominant, given the proximity of the Belém market for producers. Cultivation of secondary growth areas has been common for decades, and islands of mature forest are rare. Tomé-Açú has experienced the most intensive agriculture of the five sites (a black pepper monoculture until the late 1960s), and for the past two decades has been associated with agroforestry development carried out by the Japanese colonists who have lived there since the 1930s. It is now experiencing the start of pasture formation. Finally, the Colombian Vaupés site at Yapú, populated by indigenous Amazonians, is characterized by more traditional long-fallow swidden cultivation based on bitter manioc.

FIGURE 5-2 Research sites in Amazonia of the Anthropological Center for Training and Research on Global Environmental Change (ACT), Indiana University.

Distribution of Research Locations

Figure 5-2 shows the locations of the five study areas discussed above, and Plate 5-1 (after page 150) shows Landsat images of each location. In each region, areas representative of the major vegetation types, including different forest types and fallows, are selected for sampling. Altamira is represented by 20 sites (18 fallows and two forests), Marajó by 14 sites (10 fallows and 4 forests), Bragantina by 19 sites (16 fallows and 3 forests), Tomé-Açú by 13 sites (12 fallows and 1 forest), and Yapú by 8 sites (5 fallows and 3 forests), for a total of 74 sites. The detailed soil and vegetation inventories permit careful characterization of each location.

Vegetation and Soil Inventory and Processing

Our strategy is comparable across the 74 sites. The majority of plots and subplots are identical in size and shape, allowing cross-comparison and integration at the level of plot, site, and location. In most cases (except mature forest), the area sampled per site is 1,500 m^2. Plots and subplots are randomly distributed, but nested inside each other to account for the detailed inventory of trees (diameter at breast height [DBH] greater than or equal to 10 cm), saplings (DBH 2-10 cm), seedlings (DBH less than 2 cm), and herbaceous vegetation. In the plots, all the individual trees are identified and measured for DBH, stem height (height of the first major branch), and total height. In the subplots, all individuals (saplings, seedlings, and herbaceous vegetation) are identified and counted, and diameter and total height are recorded for all individuals with DBH equal to or greater than 2 cm.

Species identification is carried out by experienced botanists in the field and checked at the herbarium in Belém, Pará. Botanical samples are collected from half of all species identified to ensure accuracy of taxonomic identification. At each site, soil samples are collected at 20-cm intervals to a depth of 1 m. Soil samples are analyzed at the soil laboratories in Belém for both chemical and physical properties. A stand inventory table, including absolute and relative frequency, density, dominance, basal area, importance value, and stem and total height, is prepared for each of the inventoried sites.

A soil fertility index summarizing differences among regions is used (Alvim, 1974). It is important to note that our comparisons take into account only upland soils of the Marajó site. The more fertile floodplain is not included in this analysis since it is not comparable at this level with the data of the other four locations, all of which have upland soils with very different characteristics from those of floodplains. The index aggregates pH, organic matter, phosphorus, potassium, calcium and magnesium, and aluminum (inverse value). It was prepared for each depth (0-20, 20-40, 40-60, and 80-100 cm), and an average index was prepared across depths.

PATTERNS OF SECONDARY SUCCESSION IN AMAZONIA

The data obtained using the methods described above have yielded a number of findings with regard to soil physical and chemical patterns in the study regions, variations in rates of regrowth, and stages of regrowth in Amazonia.

Soil Physical and Chemical Patterns in the Study Regions

Soil structure and texture in the study regions, as represented by the percentage of fine sand, coarse sand, silt, and clay at five depths (20-cm intervals) are presented in Figure 5-3. Coarse sand and clay are the elements most able to provide discrimination across regions. Four major textural groups can be distinguished in the study regions (see Figure 5-3). Altamira soils have a low content of fine and coarse sand at all depths (average around 10 percent) and high clay content (above 45 percent) at all depths. Although the Yapú region presents a similar textural pattern, it can be distinguished by the presence of a spodic-B horizon with low permeability and penetrability, characterized as a groundwater humic podzol (Sombroek, 1984). Marajó and Bragantina soils are rather similar in terms of sand and clay content at all depths. In both cases, average, fine, and coarse sand content are above 25 percent and average clay content is below 20 percent at all depths. Tomé-Açú soils, although similar to those of Marajó and Bragantina, are distinct in their lower content of fine sand (below 25 percent) and higher clay content (30 to 40 percent) at all depths. Therefore, while Marajó and Bragantina offer typical examples of oxisols, Tomé-Açú presents a soil type closer to an ultisol.

Differences in soil fertility are small but significant among the study regions. Altamira is clearly superior in terms of soil fertility, while differences among the others are minor. The average pH of above 5 in Altamira contrasts with the average pH of below 5 in the other regions. A pH of above 5.5 is viewed as necessary for crop productivity from all but a few domesticated cultigens, such as manioc, cowpeas, and sugarcane, that are adapted to low-pH conditions. However, among the regions with lower-pH, less-fertile soils, the soils of Marajó and Yapú have lower pH (below 4.4 in the first 20 cm or plow layer) than do those of Bragantina and Tomé-Açú.

Combined analysis of aluminum and calcium/magnesium content further distinguishes fertility among the five regions. Yapú is the most nutrient-limited region, with the highest aluminum concentrations and the lowest concentrations of calcium and magnesium. This pattern is reinforced by the low availability of phosphorus. High aluminum saturation tends to limit absorption of other nutrients, especially calcium and magnesium, because of impeded root development (Lathwell and Grove, 1986). Phosphorus is considered the most limited nutrient in Amazonia, frequently found only in trace quantities (below 1 part per million). It is low at all the sites, although Altamira has slightly larger amounts than the other regions. No significant differences are found among regions in the amount of organic matter. Analysis of these elements in the form of a fertility index, as shown in Figure 5-4, reveals that soil fertility is significantly different between Altamira and the other regions, but similar overall among the other four regions.

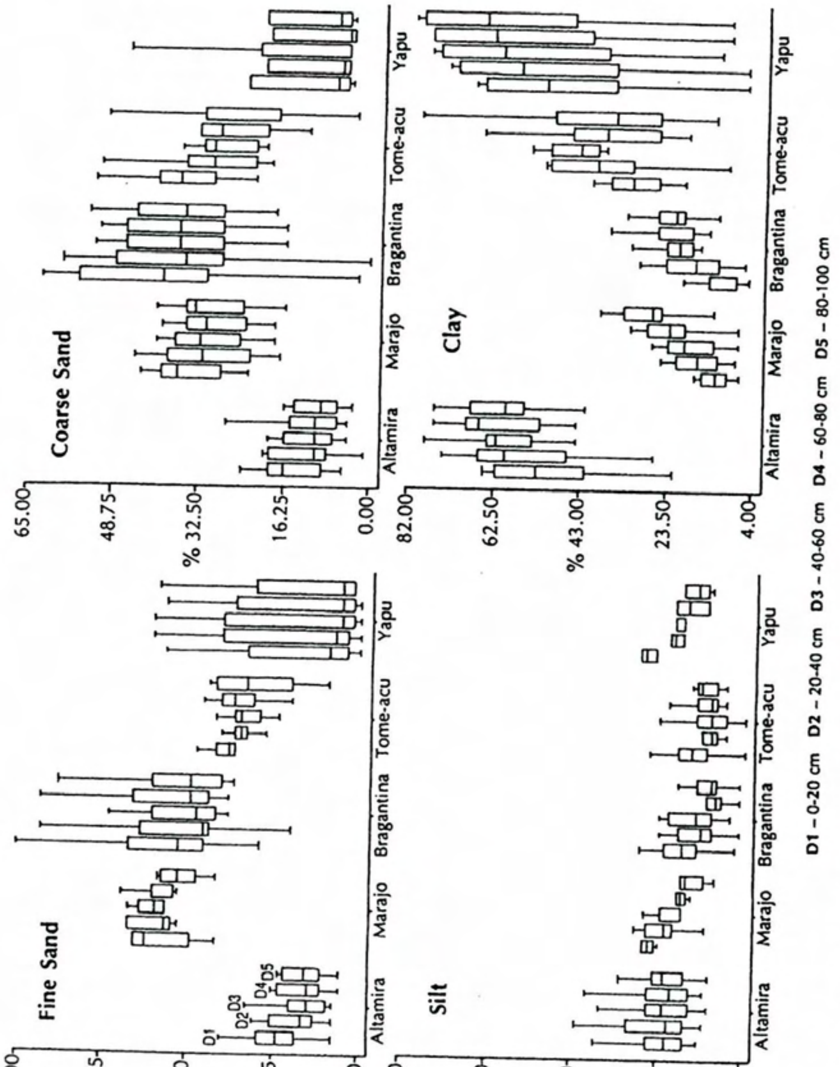

FIGURE 5-3 Soil texture by depth (Altamira, Marajó, Bragantina, Tomé-Açu, Yapú).

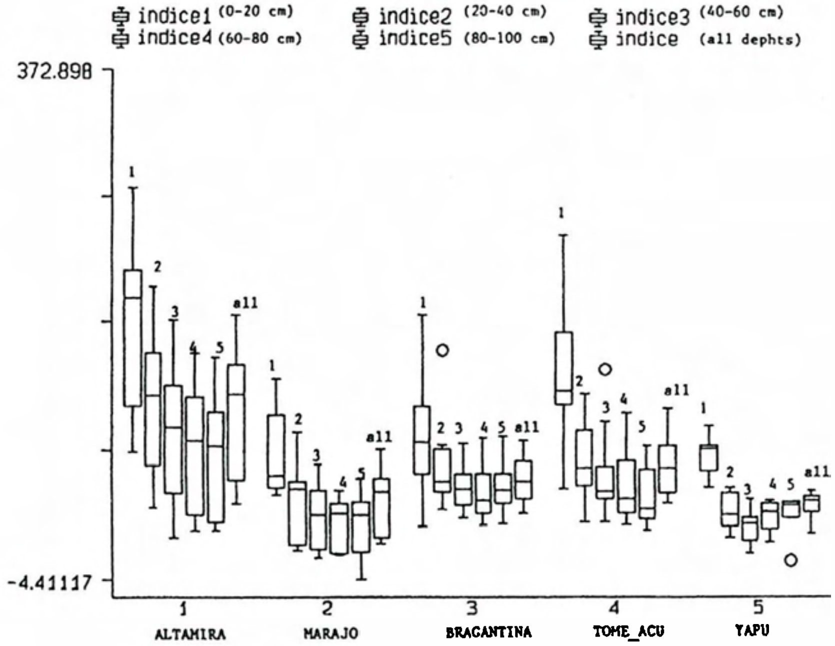

FIGURE 5-4 Soil fertility indexes for five research sites (pH + OM + P + K + Ca + Mg – Al).

Variation in Rates of Regrowth

Analysis of variance shows that soil fertility is a significant indicator of differences among regions with regard to secondary succession (adjusted r^2 = 0.69; $p < .05$) when average stand height is used as a parameter to indicate rates of regrowth. Differences in fertility clearly favor regrowth in Altamira and differentiate it from the other regions. Similar regrowth rates are observed in Marajó, Bragantina, Tomé-Açú, and Yapú. These differences are shown in Figure 5-5, where the average regrowth rate for Altamira is compared with the average rate for each other region. Altamira is the only region showing above-average rates of regrowth. During the first 5 and 10 years of fallow, Altamira fallows are 1 m higher as compared with the average fallow of all other regions. This difference increases two-fold after 15 years of fallow. Such an increase may be closely related to the faster development of trees in relation to saplings in this region. Overall, Altamira tends to reach higher canopy and lower understory biomass density at a faster rate than the other sites, indicating a more rapid pace of tree and forest structure development. This pattern is reinforced by the differences in family diversity between Altamira and the other regions. Overall.

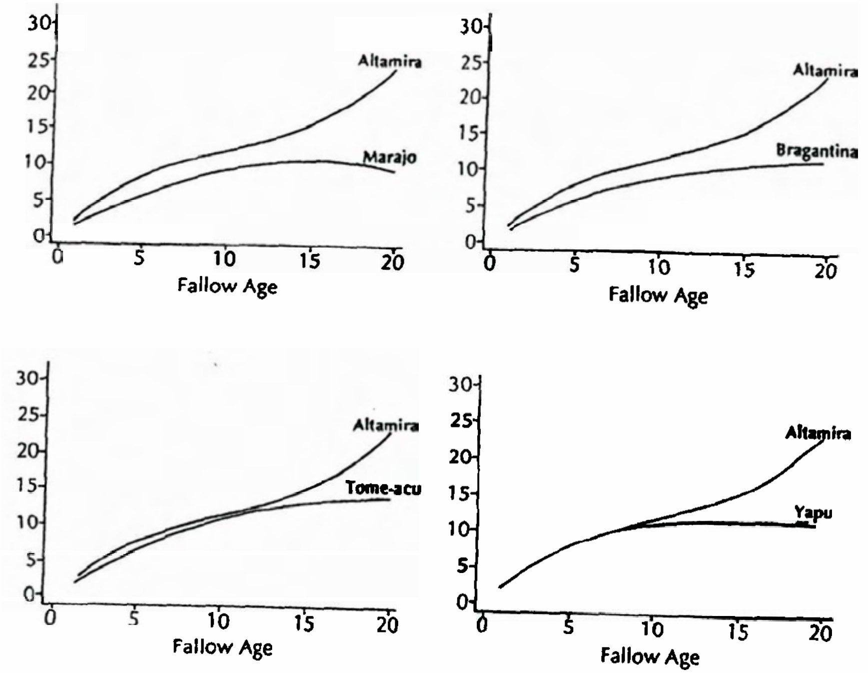

FIGURE 5-5 Height increment in secondary succession.

family diversity in the understory is higher during the first 5 years of fallow, decreases during the following 10 years, and increases again as vegetation reaches a forest-like structure. In the canopy, family diversity presents a progressive rate of increase with age. However, significant variations in this pattern can be perceived. Whereas Altamira has a lower understory diversity as compared with the other regions (especially Bragantina), it has the highest diversity of tree families, reflecting its faster canopy development. The Bragantina region in particular presents in some cases a higher degree of understory family diversity within a short-fallow swidden cultivation system. The greater diversity of saplings and herbaceous vegetation in this region is closely associated with resprouting of a specific group of families and species that has made it possible for them to survive under this intensive land-use system (Denich, 1991; Vieira et al., 1996). However, the relationships among soil fertility, fallow cycle, and indicator species are still unclear and will be the focus of attention in the near future.

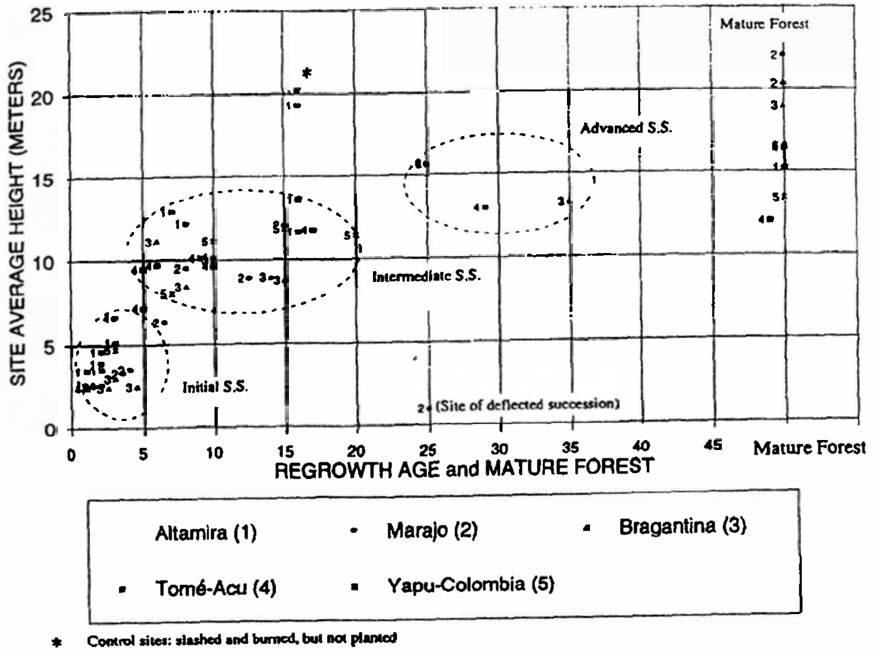

FIGURE 5-6 Regrowth stages and average stand height, ACT research sites in Amazonia.

Basin-Wide Patterns of Rates of Regrowth: Defining Stages of Regrowth in Amazonia

An important finding of this study is the definition of basin-wide stages of regrowth based on the analysis of average stand height and basal area of the study locations that correspond to distinctions derivable from spectral analysis of satellite data. While this finding may not seem to represent an important social science contribution, the detection of rates of regrowth illustrates the use of remote sensing to discriminate social phenomena, specifically land-use patterns, thus socializing the pixel (see Geoghegan et al., in this volume). Examination of the literature supports our analysis by revealing data consistent with the characteristics of our study areas. Stand height proves to be a significant discriminator of regrowth stages at the level of the study area (Figure 5-6). Three structural stages of regrowth can be distinguished: initial (SS1), intermediate (SS2), and advanced (SS3) secondary succession. These stages can be broadly associated with age classes.

SS1 is associated with a period of establishment dominated by herbaceous and woody species. Saplings are the main structural element and represent the majority of the plant biomass. Average height is 2 to 6 m. Most individuals are of a height equal to or less than 2 m during the first 2 years of fallow. In terms of basal area, this stage presents a variation that ranges from 1 to 10 m^2/ha. The majority of individuals have DBH of 2 to 5 cm. In age terms this period encompasses around the first 5 years of fallow, but it may be much longer in areas subjected to heavier land-use impacts.

SS2 can be characterized as a period of thinning of herbaceous and grass species and a rapid increase in sapling dominance, with small trees beginning to appear. While saplings account for most of the total basal area and biomass, young trees dominate the canopy structure. Canopy and understory become increasingly differentiated, but stratification is still subtle. The increase in shade during this stage is an important element in species selection. Average height is 7 to 15 m, and DBH is 5 to 15 cm. Basal area ranges from 10 to 25 m^2/ha. This period encompasses the next 10 years fallow, that is, 6 to 15 years after abandonment.

SS3 is marked by a growing stratification between understory and canopy and by the declining contribution of saplings to total basal area and biomass. Average height is 13 to 17 m; however, a considerable number of shorter (6 to 13 m) and very tall (20-30 m) emergents occur. Individuals with DBH of 10 to 15 cm are still of major importance at this stage, but a considerable number of larger individuals are present. In terms of basal area, this stage is similar to the intermediate stage. One of the reasons for this relates to the process of species selection that occurs between SS2 and SS3. Fast-growth trees of SS2 (e.g., *Cecropia* spp.) that contribute a major portion of the total basal area at this stage tend to give way to forest tree species during SS3. Therefore, instead of a progressive increment in basal area from SS2 to SS3, there is replacement of the species and individuals contributing to basal area. In age terms, this is a stage that encompasses fallows of more than 15 years. However, we found that in Altamira, this type of structure could be achieved in about 11 years.

Mature forest vegetation varies widely within the Amazon. Average height varies from less than 15 m to around 24 m. However, one can distinguish between forest and advanced regrowth by taking into account additional features that characterize mature forest vegetation. First, species composition needs to be considered as a unique discriminator of a mature forest environment. Mature forests have higher species diversity. The presence of very tall emergent trees with large diameters is also a distinctive feature. Most emergent trees have DBH above 30 cm and height greater than 15 m. Basal area in mature upland forest ranges from 25 to 50 m^2, thus providing a distinct structural difference from advanced regrowth (10 to 25 m^2/ha) that facilitates spectral separation.

This model of regrowth stages can be applied to the Amazon region if land-use intensity, landscape diversity, and soil fertility variables are taken into account at the regional and local levels. The proposed regrowth classes provide a baseline for remote sensing analysis and large-scale studies of land-use and deforestation dynamics. Structural characteristics of the vegetation such as those described above influence spectral information. Differences in average stand height can be correlated with increased absorption (i.e., lower reflectance) of the visible bands (i.e., 1, 2, 3 in Landsat TM). Likewise, these structural features lead to differing reflectance values among SS1, SS2, and SS3 and mature forest in the near- and mid-infrared bands (i.e., 4, 5, and 7). Understanding these structural/spectral relationships gives social scientists a powerful tool for studying land use and agricultural cycles of human populations. The structural parameters presented above allow one to discriminate with modest effort between areas recently and long abandoned, and to collect good-quality training samples for image-supervised classification (see Mausel et al., 1993, for a fuller discussion of spectral characteristics of vegetation types).

If one keeps in mind the general features of land-cover classes and which features have the greatest role in spectral differentiation, field research observations can generate information of considerable value to the classification of land cover. Good-quality pastures have higher visible-band reflectance than degraded pastures because of their more homogeneous surface and minimal shadow and the presence of soil as a component of reflectance (also producing a relatively high mid-infrared reflectance). A degraded pasture and initial secondary vegetation will have a lower visible-band response due to greater vegetation, less soil, and increased chlorophyll absorption. We take the categories of degraded pasture and SS1 to be equivalent: a degraded pasture is a cultural category meaningful to a rancher who sees a pasture that has been invaded by woody growth and is no longer capable of sustaining cattle; SS1 is an ecologist's category, used when a rich diversity of pioneer species occupies land that was previously cultivated or deforested and that had been characterized by a dominance of herbaceous and woody species. In degraded pasture or SS1, the near-infrared will have higher reflectance due to mesophyll reflectance, but the mid-infrared will have lower reflectance than in pasture as a result of greater absorption of water by the vegetation.

The developing canopy in SS2 has higher biomass and moisture than are found in SS1. Thus, while the visible bands will not differentiate it from SS1, the green-to-red ratio will be higher. The mid-infrared is lower than in SS1 because of increased shadow, a pattern that continues with the greater growth of the vegetation. In the advanced stages of regrowth, near-infrared and mid-infrared reflectance continues to drop because of increased shadowing and increased moisture levels in the vegetation.

Thus it is important for field work to distinguish the pattern of canopy and understory, the amount of exposed soil, the surface roughness of the vegetation, and the amount of shadowing to assist in spectral analysis of these patterns in the satellite data.

IMPLICATIONS FOR TRAINING AND RESEARCH

One of the lessons that emerges from our experience is the importance of taking time to learn the basic theoretical and methodological approaches of collaborators in other disciplines. While it may be possible to develop a clear division of labor between collaborators, the collaboration will proceed more smoothly if social scientists are familiar with the theoretical principles behind spectral information and are aware of the limitations of sensors and the sampling requirements for achieving acceptable levels of accuracy in classification. Likewise, knowing how to obtain reliable data from interviews in order to learn firsthand about the variability in human behavior and culture, as well as in plant distributions and stand structure, makes the remote sensing specialist more realistic about what can be brought back from the field and the reasons for trying to represent classes of local economic or environmental interest. It is common among remote sensing practitioners to perform field work largely to check the accuracy of categories that emerge from spectral analysis or to give them names, without much interest in changing classes that may prove to correspond poorly to field reality. The feedback from social science research and the incorporation of culturally meaningful categories are important contributions to the mapping of changes between land-cover classes and understanding of the driving forces of such changes. One of the important reasons for social scientists to play an increasing role in efforts to classify land uses with remotely sensed data is that in so doing they can begin to shift the applications of remote sensing from a mapping mode to one that seeks to explain social structures and processes—land-use dynamics, the lag time between commodity price shifts and landscape transformations, the estimation of yield from noncereal and even agroforestry crops, and the internal structure of households as revealed by the behavioral outcomes of that structure that are visible in land-cover changes.

Thus whenever possible, graduate students should be encouraged to pursue a global change graduate minor that will give them at least minimal combined exposure to the theories and methods of the social sciences, the biological sciences, and remote sensing. Lacking this, private foundations and federal agencies should be receptive to institutions wishing to support intensive training programs designed to introduce faculty and graduate students to these skills so they can participate effectively as members of multidisciplinary teams on global change. Indiana University, with support from the Tinker Foundation, has provided such training for the past 2 years to Brazilian and Mexican colleagues. Over the next several years, the NSF-funded Center for the Study of Institutions, Population and Environmental Change at Indiana University will conduct summer institutes addressing these needs, as well as continue to offer visitors month-long individualized training linking social science and remote sensing to questions of environmental monitoring and global change, particularly in forested environments.

It may be hoped that other institutions will seek additional ways of meeting the challenge of addressing what sometimes becomes a major obstacle to collaboration between social scientists and those in the remote sensing community: a lack of familiarity with the techniques of the other field and with how their distinct but complementary skills can be linked to address questions of joint interest. The role of NSF in supporting multidisciplinary work through its Program on the Human Dimensions of Global Change has been crucial to advances made in this area to date. Continued support for such work by NSF and other agencies, such as the National Institute of Child Health and Human Development (NICHD), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA), would help in further eliminating existing barriers and creating a fertile ground for additional contributions to a basic understanding of human impacts on a changing environment.

In addition to a lack of familiarity with one another's skills, another notable obstacle to collaboration between social scientists and experts in remote sensing is the continuing high price tag for obtaining high-resolution satellite data, such as data from TM and the French Système Pour l'Observation de la Terre (SPOT). Despite regular promises to the community that the price will soon return to "the price of acquisition," many obstacles remain. While archived data have come down in price, more recent TM scenes still cost over $2,000, and the recent TM scenes have had serious problems involving uncertainties over sensor calibration that make such an expense increasingly risky. A spatial resolution of 30 m or better is necessary to address many of the human-dimension questions of concern to the social sciences, yet the discussion of Earth Observing System (EOS) instrumentation has seldom included input from social scientists to ensure that concerns related to the human dimensions of global change would be given high priority in sensor design. The remote sensing community needs to develop a mechanism for liaison with the social science community that engages them both in the decision-making process regarding the kinds of earth-observing instruments needed to understand human impacts on the environment at a variety of scales. Coarse scales tend to mask both environmental and human variability—one of the main things threatened by environmental change. To understand human and biological diversity, we need instrumentation that is sensitive to these fine-scale patterns and permits the linkage of fine-scale field research to remotely sensed data (see Cowen and Jensen in this volume, who raise similar issues relevant to work in urban areas). The other notable constraint is cloud cover and shadow, the latter especially in mountainous areas. Advances in radar technology should help with this problem since clouds do not interfere with radar. However, applications of radar data to land-cover analysis will require considerable technical advances before they can be used profitably by the social sciences.

A new generation of sensors is expected in the near future (e.g., Earlybird, Quickbird, the ASTER thermal emissions radiometer, Moderate Resolution Imaging Spectroradiometer [MODIS]). It is likely that social scientists can help evaluate the capabilities of proposed sensors, as well as contribute to the discussion of data availability. As important as it is to improve spatial resolution, there needs to be a commitment by remote sensing institutions responsible for data recording that information will be stored for regions all over the world. Images from SPOT sensors, for instance, despite their higher spatial resolution, have restricted availability for isolated areas. This results in a spotty land-cover change record that renders multitemporal analysis limited in scope.

In terms of spectral resolution, there is a need to discuss the possibility of dividing bands such as TM4 and TM5 into smaller spectral regions, and to evaluate whether and how such a change could improve future studies of land-use and land-cover changes, especially those related to agriculture. By the same token, it is still unknown what kind of information would be available if a thermal band (such as TM6) were designed at a higher spatial resolution, such as 30 or 20 m. Landsat 7, which will be launched in 1998, is expected to have a 30-m thermal band.

One point that is of particular importance to remote sensing analysis but is frequently dismissed is the need to work with digital data that have been calibrated (i.e., converted to reflectance values). The implementation of technical procedures for performing such calibrations requires considerable expertise found only rarely outside of major remote sensing facilities. There would appear to be enough capability within remote sensing institutions responsible for data reception to develop relatively automated procedures that would facilitate this kind of data preparation for those, like social and biological scientists, who lack this level of laboratory or technical expertise. Even some in the remote sensing community use other procedures to get around the complex uncertainties involved in transforming digital numbers to reflectance values.

In terms of software development, there should be continuous support for the development of low-cost, interactive, yet powerful packages, such as IDRISI (developed by Clark University) and MULTISPEC (developed by Purdue University). Such packages should include a range of statistical tools allowing analysis of data for training samples to be used in supervised classification and determination of the accuracy of thematic maps. Such software packages provide an ideal tool for training social scientists, since they allow more effort to be dedicated to image analysis and interpretation than to the learning process for the oftware itself. Many social scientists are reluctant to work with digital data ecause of the slow learning curve for many remote sensing and geographic information system (GIS) packages, which translates into virtual inaccessibility f image processing to its numerous potential users. The growing capability of personal computer (PC) processors now frees new members of the community om the need to rely on the UNIX platform for working with these data. Even e powerful ERDAS Imagine image processing software is now available for the at a cost that is affordable under the most modest of grants.

CONCLUSIONS

Looking back over the past 5 years of our project linking detailed field studies to remotely sensed data, we believe that on the whole, this joint work has advanced our knowledge of important processes of land-cover change in Amazonia and our knowledge of how to link data across levels of analysis, and holds promise for further contributions in the immediate future. Without our detailed field inventories and land-use histories, we would not have been able to distinguish among three distinct stages of secondary succession in the TM images (Mausel et al., 1993; Moran et al., 1994), to distinguish floodplain forest from açaí palm managed floodplain forest (Brondizio et al., 1994, 1996), to demonstrate the linkage between soil fertility and rates of secondary succession at a more than highly localized scale (Moran et al., 1996), and to determine the relative impacts of various land-use trajectories in specific soils on species composition and biomass accumulation (Moran et al., 1996; Tucker et al., in press). The use of satellite remote sensing modified our approach to sampling so that it became more widely distributed over the landscape than it would otherwise have been. This brought us into contact with households, soils, and landscape patterns different from those we would have sampled if we had relied on traditional techniques. In turn, these contacts enhanced the regional scope of our conclusions about land use and its impact on land cover and produced statistics for areas much larger than would otherwise have been possible, while our detailed field studies allowed us to modify land-cover classes and provided enhanced discrimination. Cumulatively, our various studies have developed structural criteria that facilitate the application of these considerations in spectral analysis of satellite data for other Amazonian regions.

The linking of remotely sensed data to traditional field methods in the social and biological sciences has permitted more thoughtful sampling over a larger region, addressing questions of decadal change that could not be examined through traditional methods alone. We have documented land-cover change at five separate Amazonian locations in 5 years—a task that 10 years ago we would have thought impossible even to consider. This change has been tracked with detailed quantitative measures and accuracies of 85 to 94 percent that provide levels of confidence rarely achieved by the traditional methods of the social sciences.

Our work in Marajó, for instance, has changed how we conceptualize Caboclo populations and their engagement in the regional economy. Study of the intensification of flood plain agroforestry through a combination of household interviews, field inventory, and image classification of these areas has shown that the areal extent of agroforestry stands represents the most important production system in the region. On the one hand, it changes the characterization of the population from extractivists to intensive farmers—forest farmers. Furthermore, it shows that the level of food production can be increased without increasing rates of deforestation (Brondizio, 1996; Brondizio and Siqueira, 1997).

One can also examine changes in the densely populated Bragantina region. This area, characterized for 100 years as an area dominated by smallholders, commonly on 25-ha farms, has been undergoing transformation in recent years. What is the extent of this transformation? Is it taking place only near towns or along major roads, or is it pervasive? The use of remote sensing can help monitor these changes in land cover and help us question their desirability in social and environmental terms. At a time when cities such as Belém more than ever need a green belt to supply them with produce, the traditional sector that has supplied it may be disappearing as a result of uninformed policies or lack of support.

Altamira likewise is a landscape that poses many questions for social and environmental scientists. Will it begin to experience the same kind of logging-related fires that have plagued the Paragominas region and Borneo? Our recent work on the structure of households in the area using a property-level grid overlaid with satellite image data suggests a rapid expansion of logging beginning in 1985 and accelerating in 1988. Whereas logging was concentrated within the first 25 km from the town, in 1985, by 1991 loggers were altering areas more than 75 km from the town and desirable species have become increasingly rare closer to town. What is the spatial distribution of pasture and other economically significant land uses? What is the impact of road distance and road quality on economic activity? In some preliminary work with the near- and mid-infrared bands of TM, we detected a distinct pattern of land use in which the higher-ground farms experienced greater deforestation and land use than those occupying lower positions in the landscape. Is this a product of soil type differences along a soil catena, or of moisture saturation in lower sites? Can analyses using infrared bands provide a quick way of identifying better soils for agriculture in newly settled areas?

In the Japanese colony of Tomé-Açú there is evidence of incipient change toward the expansion of cattle ranching and away from the intensive systems of production that have characterized the past 65 years of occupation. The combined tools of socioeconomic analysis and remote sensing can provide a means of effectively monitoring such changes in culture and society that are of considerable theoretical and practical significance in terms of regional development. Tomé-Açú has long been seen as offering an example of an alternative to cattle ranching in Amazonia. Understanding of how and why this human community is shifting to cattle has considerable economic and environmental significance.

Perhaps more important to discussions of global environmental change are findings that show the large extent of carbon sequestration by secondary vegetation and its very high rate in the initial 10 years after abandonment, its spatial ariability as a function of soil fertility, and the role of land use in this process Randolph et al., 1996). In documenting the role of soils we have also found some counterintuitive results, such as very large carbon pools in the soil and in both surface and deep roots. Contrary to past wisdom suggesting that the root systems of tropical moist forests are shallow, we see the legacy of roots deep in the soil profile (Nepstad et al., 1994).

The results of the studies discussed here have led us in some new research directions, including examination of the role of the developmental cycle of domestic groups in shaping the trajectory of land use and deforestation in frontier regions and the role of community-level organizations in managing forest resources. Household composition may explain differential rates of deforestation through time better than current models focusing on migrant origins and flows. The impact of age and gender composition on strategies of land use is being examined with support from NICHD. This research will elucidate the impact of aggregate migration flows relative to that of household types within the migrant pool and the changing behavior of households through time as they mature and change in composition. A second line of investigation, under the NSF-funded Center for the Study of Institutions, Population and Global Change at Indiana University, is incorporating the community level of organization into our studies—a level that falls between the household and landscape levels on which we have focused in the past. At this level, we will be examining the organization of user groups within communities and the observable differences among groups using forest resources within different property regimes and demographic spatial distributions. This level will be linked to the field-level and landscape-level data discussed in this chapter.

In both of the above new efforts, remotely sensed data play a key role at every stage of the research—from the exploration of types of land cover, to the sampling approach taken in the field work, to the interviews with land users, to the analysis of land-use changes in time and space. These plans suggest a productive collaboration among social scientists, biological scientists, and the remote sensing community for years to come.

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NOTES

1 A notable exception is efforts by Woodwell et al. (1986, 1987) to differentiate between mature tropical forest and secondary succession. That early effort, unfortunately, encountered the limitations posed by the spatial resolution of the Landsat Multispectral Scanner.

2 Among those who have pursued the acquisition of these skills are Clifford Behrens, Bruce Winterhalder, the late Robert McC. Netting, Endre Nyerges, and Emilio Moran. There may be others that have escaped our notice. Others have preferred conducting cooperative work with remote sensing specialists (e.g., Conrad Kottak) or taking advantage of courses offered at their universities (e.g., George Morren and Thomas Rudel). The choice of whether to seek such training oneself or rely entirely on the expertise of collaborators is an important one that reflects personal style, role on the team, and synthesis goals. This is a mechanism that, if used by other social science disciplines, could substantially increase the number of scholars engaged in this type of work—although there are other modalities for achieving this goal that are discussed later in the chapter.

3 Our work would not have been possible without collaboration with the remote sensing group at Indiana State University's Remote Sensing and Geographic Information Systems Laboratory. Collaboration with Paul Mausel has been particularly valuable over several years.

4 The importance value is a measure of relative dominance, frequency, and density.

5 GPS devices provide accurate location through triangulation using at least 3, and often more, of the 24 satellites in the system.

6 Color composites made up of Landsat TM bands 5 (mid-infrared), 4 (near-infrared), and 3 visible) provide a very realistic picture of the landscape that facilitates their field use in interviews.

7 During field work we use a "synthesis table" containing the structural characteristics of a ariety of land-cover classes to guide our training sample data collection. This synthesis table inludes information such as average stand height and range of diameter at breast height for particular and-cover classes to facilitate discrimination of classes of interest. This guide is based on earlier field egetation inventories carried out in the region, but it can also be based on existing studies carried out y others.

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