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INTEGRATING AMAZONIAN VEGETATION, LAND-USE, AND SATELLITE DATA

Contents

Attention to differential patterns and rates of secondary succession can inform future policies

Deforestation in the Amazon Basin has become a matter not merely of international concern but alarm: in 1987 alone, 8 million hectares of forest were burned (Booth 1989). Primary concern has focused appropriately on the effects of this destruction on species diversity and on atmospheric chemistry. The Amazon is host to approximately half of the world's species, and its continental size and high evapotranspiration rates make it a notable influence on world climate. According to Shukla et al. (1990), removal of Amazonian vegetation on a large scale could bring about changes in the region's hydrological cycle and climate large enough that the forests may not be able to re-establish themselves.

Monitoring the rates of deforestation in Amazonia has tended to focus on dimensions of the problem that serve to alert us to the scale of the problem, but that do not necessarily address land-use and policy alternatives other than stopping deforestation altogether.

Although no more salutory policy could possibly be implemented than a complete stop to deforestation in Amazonia, such an outcome is unlikely. More feasible for reducing the rates of deforestation in the Brazilian Amazon are strategies that take into account ecological, social, and economic factors. Attention must be paid to local and external causes for deforestation, to the difficulty of environmental monitoring in a vast area with precarious infrastructure, to intraregional differences in both environmental parameters, and to what segments of the human population (e.g., peasants, ranchers, and miners) are responsible for bringing about deforestation.

The causes of deforestation in Amazonia are distinctly different from those in Indonesia, and they vary significantly even within the Amazon Basin (c.f. Kummer and Turner page 323 this issue, and the articles in Repetto and Gillis 1988). In Asia, population growth looms as a major factor, whereas in the Amazon deforestation is driven by policies that favor cattle over people as occupants of the frontier.

Amazonian deforestation has transformed Brazil into the world's fourth major contributor of carbon to the atmosphere. It ranks behind only the United States, the Soviet Union, and China (Goldemberg 1989). Destruction of Amazonian forests is responsible for the equivalent of 7% of the total carbon dioxide emissions provoked by fossil fuel emissions. Brazil contributes the lion's share of carbon emissions from deforestation, with 336 million tons of carbon per year.

This phenomenon is very recent. Salati and Vose noted in 1984 that the Amazon Basin was a large system in equilibrium, but that signs were appearing for human-induced disequilibrium coming chiefly from deforestation. Their forecast has proven all too true. According to Molion (1991), the total area altered by 1989 was 397,000 square kilometers or 10.8 % of the Brazilian Amazon forest. The most recent estimates, based on detailed examination of satellite data between 1978 and 1988, lower the estimate of total area deforested to 230,000 square kilometers, but raise the total area of forest affected by deforestation to 588,000 square kilometers, when edge effects of one kilometer into adjacent areas of forest are computed (Skole and Tucker 1993).

When did the problem actually begin and why? What policies need to be put in place that take into account the social and economic realities of Brazil? How can one monitor such large-scale land-cover change over such vast areas? Can we study these land-use changes from satellite platforms or must we rely solely on ground-level surveys? This article provides a preliminary analysis of deforestation processes linking changes in vegetation composition, land-use history, and remotely sensed data covering the period between 1985 and 1991 along the Transamazon Highway, an area where one of us (E.F.M.) began field studies in 1971 just as the area was opened up to settlement. Field studies were carried out in the summer of 1992 to better calibrate the satellite images undertaken earlier that year.

How and why did deforestation occur?

Large-scale deforestation in the Amazon Basin began with the construction of the Belem-Brasilia Highway in 1958. Occupation of land along the Belem-Brasilia was slow at first and the road cut through a broad array of vegetations, only a small part of which were tropical moist forests and rainforests. Most of them were savannas, scrub forests, and tropical deciduous forests. In the first 20 years, more than 2 million people settled along this dirt road, which was paved only in 1973. Cattle increased from near zero to more than 5 million in the same 20-year period (Mahar 1988). The land along this road that first attracted attention to the destruction of forest, especially its replacement by low-quality cattle ranches (Hecht 1980).

Road-building became even more important with the announcement in 1971 of a program of national integration that included construction of north-south (Cuiaba-Santarem) and east-west (Transamazon) highways connecting the Amazon Basin internally and linking the area to the south of the country. The goal was to move 100,000 families into the Amazon Basin in the first five years and to service them by a hierarchical network of settlements and service communities (Moran 1981, Smith 1982). However, because of the oil crisis of 1973 and changes in political priorities, many of the roads to the farms were not built and instead of the 100,000 families foreseen to participate in the Transamazon Settlement Scheme, only 6000 families came in the planned five-year period.

In 1966, a plan to encourage Brazilians to occupy the Amazon created a development agency (SUDAM) and a regional development bank (BASA) through which individuals or firms could invest in projects within the Amazon region. The small-property farmers coming to the Transamazon highway were not given access to these fiscal incentives. Instead, they received in the first few years short-term loans at favorable rates for raising annual crops such as rice, corn, and beans. But in other areas of the Amazon, larger operators (mostly cattle ranchers) could have 50% of personal and corporate income tax liability invested in approved-projects. Through these development projects, not only did they not pay taxes to the federal government but they received $3 for every dollar invested in an Amazon development project-- and got to keep all $4 and its capital gain tax-free. This sort of fiscal incentive was too much to pass up. Most of the deforestation in the Amazon Basin is traceable to this policy (Fearnside 1987a,b, Hecht 1980, Kleinpenning 1975).

Not only was this tax holiday and subsidy attractive in its own right, but a great majority of approved projects were extensive cattle ranches. The conversion of forest to pasture took place at a rate of approximately 8000-10,000 km [2] per year in the 1970s (Mahar 1988) and averaged 35,000 km2 in the 1980s (Fearnside 1989). The incentives were formally removed in the late 1980s through international pressure on Brazil.

Cattle ranches currently cover at least 8.4 million hectares and average 24,000 hectares each (Mahar 1988); some are as large as 560,000 hectares. These ranches employ few people, averaging one cowboy for every 300 hectares. According to a recent study, a typical 20,000-hectare ranch receives a 75% subsidy, and its livestock activities are profitable only when it receives the full array of tax advantages (Hecht et al. 1988). Without these advantages, a ranch cannot operate profitably nor achieve positive internal rates of return.

There can be little doubt that without the subsidies deforestation rates would have been much lower, demonstrated by the decline in rates of deforestation since the removal of most fiscal incentives and tax advantages in 1987. The conversion of forest to pasture is not the result of local population pressure, as it is often assumed by scholars unfamiliar with the peculiar political economy of Brazil (Denevan 1980). In fact, there is growing evidence that the conversion of forest to pasture leads to rural depopulation in Amazonia (Mougeot and Aragon 19811.

The two other sources of deforestation in the Brazilian Amazon are mining and timber activities. One recent large-scale mining development has begun to have a potentially devastating impact. Tax holidays were offered for the production of pig iron in the Great Carajas region, and plants were designed to operate using locally produced charcoal. Some smelters are already in operation. Annually, 610,000 hectares of forest would be cut for making charcoal for the smelters in the Greater Carajas pig-iron projects alone. The Greater Carajas area accounts for 10% of Brazil's total territory.

The importance of timber exploitation in deforestation began to be noticed only in the 1980s. In the most recent statistics, four of the six states in the region depend on wood products for more than 25 % of their industrial output (Browder 1986). In Rondonia and Roraima, wood products account for 60% of the output. The number of licensed mills has increased more than eightfold since 1965, and the annual output per mill has doubled during the same period. The Amazon region of Brazil accounted in 1984 for 43.6% of national roundwood production, compared with only 14.3 % ten years earlier (Browder 1988). The declining contribution of Asian forests to the world's demand for tropical wood products will lead to further increases in these activities in the 1990s.

Despite the inherent difficulties, timber exploitation is a form of land use that will have to be monitored from space because the Amazon Basin is so large and access to remote areas is difficult. Because most timber activity in the Amazon removes only a couple of trees per hectare, from satellite platforms it has been difficult to distinguish it from natural tree falls and gaps. Once the timber exploitation occurs, it may be possible to observe it because of mortality in the thinned-out area. As Uhl and Vieira have suggested, selective logging has a devastating impact on the surrounding forest, leading to as much as 40% mortality (Uhl and Vieira 1989).

The net result of road-building and the associated activities of farming, ranching, mining, and logging has been devastating to the tropical forests of the Amazon. This attention on deforestation, however, overlooks the fact that as soon as an area has been cut down and burned, there is rapid regrowth through sprouting, seed deposition by mechanical and faunal means, and seed survival. Field studies have shown, time and again, that forest rebounds rapidly after cutting and burning, even after a few years of light grazing (Buschbacher et al. 1988, Uhl and Buschbacher 1985).

Even in relatively oligotrophic areas, forests return because many of the forest species are tolerant of the low-nutrient stocks and acidity found in many of the soils of Amazonia. Lost nitrogen is replenished by leguminous species, which are common in many parts of Amazonia. Regrowth of forest species is more often inhibited by seed and sprout predation, loss of seed viability, and absence of seed sources than it is by soil degradation (Uhl and Vieira 1989).

A study of forest recovery on 12 abandoned pastures near Paragominas found that trees were re, colonizing 11 of the 12 sites. It seems that when an area cleared is not large, so that nearby seed sources are available, and if repeated burnings of the same area are not undertaken to destroy the seed bank, forest regeneration is quite likely (Buschbacher 1986, Buschbacher et al. 1988). Depending on the length of time elapsed since clearing, the forms of land use, the presence or absence of fire, and the initial soil fertility at the site, regeneration after clear-cutting has ranged between 7.25 and 12.6 tons of biomass per hectare per year (Uhl 1987, Uhl et al. 1982).[1]

From farmers' points of view, it is regrowth more than declining soil fertility that stands as the most serious obstacle they face to obtain an acceptable return on their labor. Twenty years after the start of Transamazon settlement, farmers commented that they had been poorly informed by the government and the development banks. A common complaint was that, if they had only known how vigorous plant regrowth was going to prove, they may not have cleared as much land.[2]

Much of the land cleared in the past 21 years in the region of Altamira is today at some stage of secondary succession. The cost of keeping an area cleared of pioneer species is prohibitive to most farmers. Given this experience of farmers in the region, it is socially and economically important, as well as ecologically significant, to examine the processes of land use that lead to differential outcomes in rates of secondary succession in Amazonia. Past land-use practices have been economically and biologically wasteful. Studying the processes of land use and the patterns of regrowth can inform future policies toward a greater synergy with the natural dynamics of succession.

Using Landsat satellite data

How is one to arrive at an accurate understanding of change in land use and land cover in an area as vast as the Amazon Basin? The region is the size of the continental United States. It is all too common to claim highly localized site-specific research as representative of this vast basin. How might sampling be undertaken that represents the range of physical, biological, and socioeconomic variations present?

Our approach has been to undertake a multidisciplinary project focusing on the processes of land-cover change following deforestation along a fertility gradient from eutrophic to oligotrophic conditions. Current ongoing research by anthropologists, geographers, and forest ecologists at Indiana University and Indiana State University, with the collaboration of Brazilian botanists, climatologists, and soil scientists at EMBRAPA (Empresa Brasiliera de Pesquisa Agropecuaria; Federal Agency for Agropastorial Research)/ Centro de Pesquisa Agroflorestral do Tropico Umido; and CPATU (Center for the Study of the Humid Tropics) addresses these processes through multitemporal analysis of Landsat satellite images complemented with field studies of stand structure and history of land use in specific fields.

Analysis of the satellite data allows us to ask questions about dimensions of the region's ecology that are harder to address by ground-level surveys, limited as they must be in the total area covered. Unlike site-specific studies, satellite data permits a regionally broad analysis rarely possible with field methods alone. Field studies can verify the accuracy of the satellite image analysis and assure the accuracy of the regional assessment.

The long-term objective of this research is to use satellite data to discover areas that are experiencing rapid regrowth and then to find out through field studies the impact on rates of regrowth of different land-use practices, soil types, and sizes of area cleared. This approach is based on the assumption that local strategies have a greater potential of being used in the region, because they are products of the political, economic, and environmental setting within which they came about, rather than idealized solutions generated elsewhere. It is an eminently inter-disciplinary project requiring expertise from agronomy, anthropology, the biological sciences, climatology, forestry, geography, and other fields.

The use of remote digital images has become an indispensable tool in environmental assessment and resource management (Heller 1985). The feasibility of using this technology to map and manage tropical forest resources has been demonstrated (e.g., Baltaxe 1980, Danjoy and Sadowski 1978, Eden and Parry 1986, Green 1983, Lanly 1981). The number of projects carried out in Latin America has grown steadily. Remote sensing seems particularly valuable for work in inaccessible regions, such as the Amazon Basin, where assessment of vegetation and soils by field studies is difficult (Danjoy 1977, 1984, Myers 1988, Shimabukuro et al. 1984). Studies by Malingreau and Tucker (1988), Woodwell et al. (1987), Shukla et al. (1990), and Stone and Woodwell (1988) call attention to deforestation rates in Rondonia and in the transitional forests of southern Para--the areas most profoundly affected by cattle ranching and land speculation in Amazonia. Not often mentioned in recent assessments of the processes of deforestation is the reclaiming of cleared areas by forest vegetation. Malingreau and Tucker (1988) have called for more detailed satellite data analysis to better quantify regrowth processes during the so-called pasture degradation stage (i.e., succession). It is toward this goal that this analysis is geared.

Our current research takes a more fine-grained view than is sometimes undertaken in Landsat satellite image analysis, concerned as we are with discovering approaches to restoration of deforested area rather than with documenting the extent of deforestation per se. In such an approach, it is imperative that fields as small as one hectare be accurately identified. We use Landsat Thematic Mapper (TM), which has 30-meter resolution that permits observations with pixels of approximately 0.09 hectares. Data for the years since 1984 are available, and the two midinfrared spectral bands facilitate vegetation cover analysis and make it possible to differentiate between successional stages. In this article we rely on two scenes, for 1985 and 1991, of Landsat TM. Other dates have been acquired and results will be reported later. The earlier presentation of the data in this article, at the 1992 Ecological Society of America meeting, was the first report, to the best of our knowledge, of secondary successional forest age classes being distinguishable from satellite data. At best, earlier reports had been able to simply distinguish between forest and deforested land in Amazonia. Reliance on NOAA's Advanced Very High Resolution Radiometer and on Multi-spectral Scanner Landsat data, with less fine resolution than the Thematic Mapper, was in large part responsible for this problem in monitoring secondary successional dynamics.

Analytical procedures for satellite data analysis

The steps followed in the analysis of satellite data include the identification of land-cover classes of interest, the selection of representative samples or "training sites" for each class derived from fieldwork and other sources (e.g., accurate maps and aerial photography), the development of representative spectral statistics that constitute a given distinctive spectral pattern, or signature, and classification of the data. We chose to begin this long-term research in the relatively eutrophic areas along the Transamazon highway, because this approach would permit the observation of these successional processes in the relatively short period covered by Landsat satellites. The Altamira area of the Transamazon Highway, like Rondonia, has some sizable patches of eutrophic soils such as alfisols that can be expected to enhance regrowth, compared with less-favored areas.

Ground information collected during the 1992 fieldwork was used to define training areas from which spectral signatures were developed for further classification of the entire 1654 x 1806 pixel Altamira study area (i.e., 267,378 hectares for the eastern portion and 233,466 for the western portion). A majority of the spectral data used to define classes was derived from two subsites in the eastern portion (designated here as Alta km 23 and Alta km 46), from which a substantial body of ground information was collected during 1992. Ground information from three other Altamira subsites was also used. Thus, the classification results presented in this article define spectral signatures informed by ground truth sufficient to assure accuracy. Accuracy of more than 92.2% was obtained for most land-cover classes of interest (Mausel et al. 1993). Although it is possible to develop land-cover classes without detailed ground truth, using unsupervised classification, such a procedure is highly inaccurate in an area as diverse as the Amazon. Future incorporation of additional ground information and data on soils, terrain, roads, vegetation surveys, and geographic-information-system approaches may lead to refinement of some of the results presented here.

The remote sensing methods used to develop information began with relatively high-dimensional clustering (i.e., unsupervised classification) of small areas (less than 15,000 pixels) using six-band TM data. In these small subareas, 25-40 clusters were developed, each of which contained several samples of known character derived from 1992 ground observations and land-cover histories. Classes dominating sample areas of known character were noted, and their statistics (i.e., means, variance, and correlation) saved for use as training statistics representative of that feature in a supervised classification. Similar spectral statistics were acquired for polygons (i.e., areas of 20-100 pixels) whose land-cover character was known from field observations.

The various sets of spectral statistics (i.e., the signatures) of each class of interest were evaluated from a theoretical perspective (i.e., does the six-band spectral pattern make sense from the physical/spectral nature of a given feature?) and from the available ground information. In this fashion, a conceptual spectral model was developed that defined the nine land-cover classes. The model is a theoretically logical system that considers the reflection and absorption characteristics of the physical components that comprise each class. Figure 1 illustrates the spectral pattern of major classes. It attempts to account for chlorophyll absorption in the visible TM bands (TM bands 1-3), for mesophyll reflectance in the near infrared TM band 4, and for both plant and soil water absorption in the midinfrared bands 5 and 7. In addition, land cover and plant geometry were found to enhance class differentiation.

For example, the moist forest signature is distinctive from other classes: it has very low reflectance in band 3 due to maximum chlorophyll absorption, modest band 4 reflectance, and very low reflectance bands 5 and 7. The high biomass and water content associated with moist forest vegetation helps explain the pattern of high absorption of visible and midinfrared energy, but it does not explain the subdued near-infrared reflectance--which is often highly correlated with large bio-mass--nor the very low visible red and midinfrared values.

Plant canopy geometry and density, often expressed in the form of shadow, are responsible for the subdued near-infrared reflectance. Rain-forests and moist mature forests have more shadowing than do early successional, pasture, or crop vegetation. Shadow is a spectral trap for incoming energy; thus, highly shadowed features have depressed reflectance, particularly in the longer wavelengths. This type of analysis, linking spectral responses to physical/biological structure, gave coherence to the spectral model and to the distinct signatures illustrated in Figure 1.

Transamazon Highway vegetation change

A significant portion of the moist forests and liana forests in this region have been converted to agricultural areas. Field crops, tree crops, and pasture have been introduced since the roads were built in the early 1970s. In our field study of Altamira, we studied 22 secondary successional areas in 1992 and 14 areas in 1993 at various stages of regrowth and with different types of land-use history and soil type. For each area, we sampled the species composition, stem.height, total height, percent of ground cover, and diameter at breast height, including understory vegetation, which will permit assessment of species frequency, density, and dominance. These data are reported elsewhere.3,4 They indicate that biodiversity is lowest in mechanically cleared pasture, followed by manually cleared pasture, and then by the more common pattern of crops followed by pasture. Suffice it to say that tree species diversity within the first ten years is in the 50 to 75 species range in natural regrowth. Interestingly, in two cases where a farmer developed an agroforestry system around mahogany and cedar, we found considerable diversity as well due to sprouting. The agroforestry site had species diversity comparable to that of areas of natural growth. These cases suggest that it may be possible to select species that can grow vigorously alongside the sprouts of the native species.

Between 1985 and 1991, considerable areas have gone from bare soil (13.19 % of the eastern portion of the study area and 7.58% of the western portion) to various degrees of secondary succession, crop, pasture, and other vegetation cover (Table 1). Forest declined by slightly more than 1% annually in the eastern portion of the Altamira site-- a rate higher than the Amazon-wide average of 0.4%, according to the latest estimates of Skole and Tucker (1993). The western portion of Altamira was closer to the regional average in deforested area. The surprisingly large area of relatively bare soil at the time of the 21 July 1985 Landsat scene (Figure 2a) was said by local people interviewed to have been the result of a very dry season during which most pastures turned yellow and wilted. Indeed, the rainfall for July 1985 was 10.5 mm, in contrast to the mean for that month of 65.7 mm.[5] Cropland and pastureland have increased, but these areas' location suggests that they had already been cleared for crops and do not represent new deforestation.

More striking, however, is the large increment in secondary successional land cover, approximately 32,000 hectares for the eastern part of the study area in that time period, compared with the area deforested of 19,000 hectares (see Table 1 and Figure 2a,b). The increase in secondary succession is less dramatic in the western portion of the study area (Table 1), but deforestation as well has been much less to date (30% versus 43 %). However, the percentage increases for intermediate secondary succession are consistent. Some of the early successional areas are the proverbial degraded pastures that have been invaded by woody species. The intermediate secondary successional class is made up of areas abandoned for 6-10 years, with woody growth of more than 8 meters. Many of the trees there have attained significant diameters at breast height.

For a closer examination of the land-use changes, we focus now on two study subsites that have been evaluated using ground information. Both subsites represent mature well-developed areas of pioneer agriculture along, and intermittently perpendicular to, the Transamazonian highway. The km 46 site (see Figure 3a,b) is 9.0 x 7.5 km in area with a large urban settlement that gives it a larger area of bare land cover than the km 23 site (Figure 4a,b). The km 23 site is 6.0 km x 12.0 km in an area with no urban community. Both sites have similar complexity of forest, pasture, crop, and succession vegetation features, but site km 23 has the additional features of standing water (reservoir) and wetlands. These two areas have been settled by colonists for almost 20 years (Moran 1981). Some areas in km 23 (Figure 4) were occupied even before the 1970s. As a result, there is less remaining mature forest (44.8 %) in km 23 than in km 46 (56.75%). Approximately 57% of what was originally virtually undisturbed tropical moist forest is now in various stages of pasture, secondary succession, and crop.

Despite their proximity and their similarity in physical conditions, there are interesting differences between the two sites. Km 46 is a service center community, with brick factory, lumber mills, and other industries. Some of the earliest forest areas cut for pasture or crop were abandoned to secondary succession and are at a stage where they are gradually becoming dense forest. The higher incidence in km 46 of absentee owners who run businesses in town may partly explain the greater area in pastures in this area, and also the greater neglect of them that results in greater proportions becoming degraded pastures. There is also less cropland in cultivation (4.17% versus 6.53%) in km 46 than in km 23, a pattern consistent with the greater number of business owners in km 46. There are larger patches of medium- to high-fertility soils in km 23 than in km 46 (Moran 1981).

At what is still only the beginning of integrating our detailed field data, it is already possible to differentiate in the satellite data secondary growth of 10-15 years (advanced secondary succession) from forest, and also to differentiate secondary growth of 6-10 years (which in this area of eutrophic soils can mean a canopy height averaging more than 8 meters) into a distinct class that we have called intermediate secondary succession. At 15 years (i.e., advanced secondary succession), the difference in reflectance seems to be getting close to mature forest in these eutrophic areas. Figure 5 illustrates the differential signatures for forest and stages of secondary succession.

However, these are some of the most fertile areas of the Amazon. In poorer patches that we came across in km 23 and km 46, we observed 15-year secondary growth that was barely taller or thicker than 2-year regrowth in more eutrophic patches. Research of our team for the next three years will focus on several oligotrophic sites to contrast successional rates in these areas with those documented at Altamira. Although we have not been able to incorporate all the areas sampled, it has been possible to differentiate between relatively clear pastures and those with considerable degradation through invasion of woody species (initial secondary succession). In this colonization zone between 1985 and 1991, we found few cases of land going from cropland directly back to secondary growth without going through a pastureland period. Traditional populations living in the area (i.e., caboclos; cf. Moran 1974) are among the few who may leave an area fallow without using it as a pasture.

This analysis has identified the basic land cover of the subsites. Additional analyses undoubtedly will adjust boundaries, adjust class designations, and add new classes, but Figures 1 and 5 provide a good idea about the types of features identifiable using computer analysis of TM data supported by ground-based information. Tables 2 and 3 summarize the land-use/land-cover changes for each site. Both sites have similar patterns of distribution for the area's most dominant features.

Despite more than 20 years of deforestation and land-cover changes, undisturbed forest is still the most common feature. Intermediate secondary growth is the most common culturally induced land-cover type. It is possible these areas of secondary growth could be cut and cleared again under the right economic conditions--or continue their trajectory toward advanced and mature stages of forest development.

Pasture was third in importance in 1991. These pastures are a mixture of dense grassy materials of various heights mixed with some trees. Areas of relatively uninvaded pastures are small and exist for only the first year or two after being formed, but their tendency toward initial secondary succession makes this class a difficult one to predict gaining in the future. Advanced secondary succession represents areas in which forests were culturally (or possibly naturally) disturbed and have regrown to a state that is similar to undisturbed forest in biomass and plant geometry. This cover type is the fourth most abundant in the subsites and locates a majority of the areas that were subject to early cutting and abandonment/succession. It is these areas that can be considered reforested or nearly reforested. The area devoted to crops is small, suggesting the poor returns to farmers from cultivation, transportation problems, and the persistent favoring of cattle ranching among credit givers in banks and government agencies.

Pastures returning to forest are the dominant features in the culturally modified areas. This finding contradicts the perception that uninvaded pastures are becoming the dominant feature of the Amazonian landscape.

Conclusions

The successional process that cattle ranchers decry as "pasture degradation," ecologists welcome as return of the forest. This process occurs at different rates throughout the basin, as a function of how thoroughly the area cleared was burned, the viability of the soil seed bank and sprouts, how much biomass remains unburned to provide slow nutrient release to invading species, the subsurface nutrient content of soils, the degree of slope present, and other variables that constitute the growing conditions to a range of forest species.

The increase in area returning to forest is not a sign of a rising conservation ethic but, rather, a result of the decline in subsidies and the less-favorable credit policies since 1987, of the absentee status of some of the owners of larger properties, and of the recognition of the difficulty and costliness of controlling weed invasion over large areas. Correlations of the changes in areas of forest cleared with shifts in credit availability and in other policies that have encouraged people to clear more forest in the past will be sought in the near future, to quantify the net effect of policy shifts on rates of deforestation and perhaps even to determine what forms of credit are associated with more and less destructive policies.

Over the years, many scholars have suggested that an effective way to reverse the tendency toward very large landholdings (i.e., latifundia) in Latin America would be to tax landowners for their properties. In some countries, such as Brazil, there are already laws in the tax code that, for example, charge 25% for capital gains tax on land sales, but the taxes are not collected. Its collection is likely to have the most direct impact on the current wave of land speculation by penalizing rapid turnover of properties, rather than their use for productive purposes. Also effective would be institution and collection of an annual progressive property tax on landholdings. Taxation could also be instituted that gave favorable tax rates to those who buy degraded areas to reclaim them for farming, ranching, or forestry activities.

Technical and scientific assistance in demarcating areas as biological and indigenous reserves, assistance in training of forest rangers, equipment to facilitate monitoring work by forest agencies, and training in the use of economical monitoring techniques such as the use of satellite digital data have an important role to play in the future of Amazonian forests. The rapidly growing conservation organizations in Latin America need technical help so that they can fight their own battles internally, rather than rely on foreign conservation groups to speak for them. The issue of national sovereignty over Amazonian territories is a sensitive one, and those wishing to protect the forests need to recognize the political dimensions of territoriality. The work of scientists investigating native systems of forest use and conservation needs research support (cf. Moran 1993, Posey and Ballee 1989). This work is consistent with technical recommendations favorably commending agroforestry approaches to forest management and recognizes the importance of local ecosystems' variability.

Specifically, it is important to be able to determine land-use patterns and sequences of patterns in order to understand the agricultural structure of an area and to assess its character within its environmental context. It is important to know how deforested areas regenerate after cropping or pasture use. Does a regenerating forest require 15, 25, or 100 years to become similar to the original forest? How does the history of a site's land use influence the rate of regrowth? How does soil quality affect the rate of regeneration?

Knowledge about the variations in pasture, from new clean pasture to successional forest, can be important in assessing the agricultural land-use characteristic of an area as well as to aid in monitoring reforestation rate potential. These considerations require a different kind of satellite data analysis than do Amazon-wide assessments of deforestation (e.g., Skole and Tucker 1993), excellent and necessary as these may be. Complementary approaches to research, especially those linking detailed site-specific studies to regional processes, are needed. Biological scientists are more likely to find the linkage of fieldwork with satellite data analysis, as has been reported in this article, useful in contributing to their understanding of succession, than methods that are less site specific. Rates of succession vary as a product of management and environmental parameters, and they should be a factor in granting land-use permits in the future.

The forces leading to deforestation vary from place to place within the Amazon. Ranching is dominant in southeastern Amazonia and more recently in Rondonia. Mining has grown in importance with development of pig-iron smelting and the design of smelters that consume locally produced charcoal. Hydroelectric development has inundated Significant areas of the region and brought about relocation of both native and nonnative populations. Colonization seems to have been a significant driving force in deforestation in Rondonia at the outset, replaced now by cattle ranching and land speculation. Global approaches that fail to take into account these intraregional differences will miss the mark. Global effects have variable local dynamics that must be addressed if the effects are to be brought under control.

Future research will need to be more sensitive to internal differences in climate, soils, forest type, economic activities, and socioeconomic and political forces. Toward achieving this goal, the use of satellite and radar data, in combination with multidisciplinary field studies, promises to serve a useful role not only in monitoring rates of change in forest cover but also in identifying local solutions to environmental problems of global import. The progress reported here in developing signatures for changing land cover, and in particular the differentiation achieved with regard to growth rates in secondary successional forests, demonstrates the value of collaboration among biological, physical, and social scientists using appropriate techniques to address the relation between global, regional, and local environmental change.

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Table 1. Land-cover changes in Amazonia, 1985 to 1991.

	1985		1991		
Location and feature	Percentage	Hectares	Percentage	Hectares	Percentage change
Eastern Altamira					
Water	5.23	13,991	5.27	14,091	0.76
Wetland	0.16	428	0.17	455	6.31
Bare	13.20	35,285	1.38	3689	-89.55
Crop	2.02	5404	4.26	11,390	110.77
Forest	64.30	171,901	57.10	152,673	-11.19
Pasture	1.24	3318	7.03	18,797	466.52
Initial secondary succession	7.35	19,662	8.45	22,593	14.91
Intermediate secondary succession	5.26	14,071	11.84	31,658	124.99
Advanced secondary succession	1.24	3318	4.50	12,032	262.63
Total	100	267,378	100	267,378	
Western Altamira					
Water	0.05	117	0.05	117	0
Wetland	0.05	120	0.05	120	0
Bare	7.58	17,697	0.58	1354	-92.39
Crop	1.15	2685	1.21	2825	5.21
Forest	74.60	174,162	70.53	164,661	-5.46
Pasture	2.07	4833	3.48	8125	68.12
Initial secondary succession	7.64	17,837	8.06	18,817	5.50
Intermediate secondary succession	5.09	11,883	13.04	30,443	156.19
Advanced secondary succession	1.77	4132	3.00	7004	69.51
Total	100	233,466			

	100	233,466

Table 2. Land-cover changes at Altamira subsite km 23, 1985-1991.

	1985		1991		
Feature	Percentage	Hectares	Percentage	Hectares	Percentage change
Water	1.79	129	1.49	108	-11.17
Wetland	0.15	10	0.09	6	-40.00
Bare	24.99	1813	1.68	122	-93.28
Crop	3.60	261	6.53	474	82.50
Forest	44.80	3251	42.41	3077	-5.33
Pasture	2.18	158	8.52	618	290.83
Initial secondary succession	12.18	884	12.69	921	4.19
Intermediate secondary succession	8.72	633	20.19	1465	132.68
Advanced secondary succession	1.59	115	6.38	463	301.26
Total	100	7254	100	7254	

Table 3. Land-cover changes at Altamira subsite km 46, 1985-1991.

	1985			
Feature	Percentage	Hectares	Percentage	Hectares
Water	0.02	1	0.06	6
Wetland	0.01	1	<0.01	1
Bare	18.88	2307		
Crop	3.20	391		
Forest	56.75	6936		
Pasture	1.54	189		
Initial secondary succession	10.54	1288		
Intermediate secondary succession	7.27	888		
Advanced secondary succession	1.78	218		
Total	100	12,219		

2.35	287
4.17	510
54.61	6674
7.93	968
11.42	1395
14.51	1773
4.95	605
100	12,219

Percentage change
200.00
--
-83.85
30.31
-3.77
414.94
10.63
99.59
178.09

GRAPH: Figure 1. Spectral signatures of features in Altamira from supervised classification based on a Landsat Thematic Mapper (TM) 1991 scene and field study. Crop and intermediate succession are separable in TM band 4. Bare soil is the only condition that is separable in TM bands 1, 2, and 3. Water and wetland are largely separable only in bands 5 and 7; but forest and wetland are indistinguishable if one relies solely on band 7. This consideration is important in that use of photographic products from Landsat often relies on only a single channel, or a couple of channels, in printing out an image-- rather than working with most of the bands in seeking out separable features.

GRAPH: Figure 5. Spectral signature of forest and secondary successional classes in Altamira based on 1991 Landsat TM scene and field studies. Although forest and pasture are similar in band 4, they separate out clearly in bands 5 and 7. Initial, intermediate, and advanced secondary succession are more clearly separable in band 5 and less so in bands 4 and 7. Forest and secondary succession can also be separated in band 4.

MAPS:Figure 2. Distribution of nine classes derived from supervised classification of Landsat TM for the area from the town of Altamira to 70 kilometers west of town along the Transamazon Highway. Left, 1985; right, 1991. The river on the right is the Xingu.

MAPS:Figure 3. Distribution of nine classes derived from supervised classification of Landsat TM for a subarea near kilometer 46 west of Altamira and site of the next-largest urban settlement along the Transamazon highway. Top, 1985; bottom, 1991.

MAPS: Figure 4. Distribution of nine classes derived from supervised classification of Landsat TM for a subarea near kilometer 23 west of Altamira. Left, 1985; right, 1991

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