Journal of Biogeography, **29**, 737–748

Predictors of deforestation in the Brazilian Amazon

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Abstract

Aim and Location We assessed the effects of biophysical and anthropogenic predictors on deforestation in Brazilian Amazonia. This region has the world's highest absolute rates of forest destruction and fragmentation.

Methods Using a GIS, spatial data coverages were developed for deforestation and for three types of potential predictors: (1) human-demographic factors (rural-population density, urban-population size); (2) factors that affect physical accessibility to forests (linear distances to the nearest paved highway, unpaved road and navigable river), and (3) factors that may affect land-use suitability for human occupation and agriculture (annual rainfall, dry-season severity, soil fertility, soil waterlogging, soil depth). To reduce the effects of spatial autocorrelation among variables, the basin was subdivided into >1900 quadrats of 50×50 km, and a random subset of 120 quadrats was selected that was stratified on deforestation intensity. A robust ordination analysis (non-metric multidimensional scaling) was then used to identify key orthogonal gradients among the ten original predictor variables.

Results The ordination revealed two major environmental gradients in the study area. Axis 1 discriminated among areas with relatively dense human populations and highways, and areas with sparse populations and no highways; whereas axis 2 described a gradient between wet sites having low dry-season severity, many navigable rivers and few roads, and those with opposite values. A multiple regression analysis revealed that both factors were highly significant predictors, collectively explaining nearly 60% of the total variation in deforestation intensity ($F_{2,117} = 85.46$, $P < 0.0001$). Simple correlations of the original variables were highly concordant with the multiple regression model and suggested that highway density and rural-population size were the most important correlates of deforestation.

Main conclusions These trends suggest that deforestation in the Brazilian Amazon is being largely determined by three proximate factors: human population density, highways and dry-season severity, all of which increase deforestation. At least at the spatial scale of this analysis, soil fertility and waterlogging had little influence on deforestation activity, and soil depth was only marginally significant. Our findings suggest that current policy initiatives designed to increase immigration and dramatically expand highway and infrastructure networks in the Brazilian Amazon are likely to have important impacts on deforestation activity. Deforestation will be greatest in relatively seasonal, south-easterly areas of the basin, which are most accessible to major population centres and where large-scale cattle ranching and slash-and-burn farming are most easily implemented.

Keywords

Amazon, Brazil, deforestation, government policy, habitat fragmentation, highways, human population size, rainfall, rainforest, roads, soil fertility.

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INTRODUCTION

The Amazon basin sustains about 60% of the world's remaining tropical rain-forest and plays vital roles in maintaining biodiversity, regional hydrology and climate, and terrestrial carbon storage (Salati & Vose, 1984; Fearnside, 1999; Houghton *et al*., 2000). This region also has the world's highest absolute rate of deforestation. In Brazilian Amazonia, which encompasses about 70% of the basin, deforestation rates since 1995 have averaged nearly 2 million ha year^{-1}, the equivalent of seven football fields per minute [Brazil's National Institute for Space Research (INPE) 2000; Laurance *et al*., 2001a].

In addition to outright deforestation, large expanses of forest are being degraded by habitat fragmentation, edge effects, selective logging, surface fires, illegal gold mining, overhunting and other activities (Fearnside, 1990; Laurance, 1998; Cochrane *et al*., 1999; Nepstad *et al*., 1999a). One key study estimated that in 1988, the area of forest in Brazilian Amazonia that was fragmented (< 100 km^2 in area) or prone to edge effects (< 1 km from forest edge) was over 150% larger than the area actually deforested (Skole & Tucker, 1993). Moreover, nearly as much Amazonian forest is being selectively logged each year (1.0–1.5 million ha year^{-1}) as is being deforested (Nepstad *et al*., 1999a).

Given the global significance of the Amazon, increasing attention has been focused on documenting the pattern and pace of deforestation in the region, and on identifying the proximate and ultimate drivers of forest loss and degradation. These efforts fall into four rough categories. The first are remote-sensing studies that quantify the rate and spatial extent of forest loss. For example, INPE has used Landsat Thematic Mapper data to map deforestation annually in Brazilian Amazonia since 1988 (e.g. INPE, 2000). Other studies based on remote-sensing have quantified deforestation patterns in specific regions (e.g. Alves *et al*., 1999; Maki *et al*., 2001; Steininger *et al*., 2001a, b) and estimated carbon flux from Amazonian deforestation (Houghton *et al*., 2000).

Studies in the second category evaluate the effects of government policies and development activities on deforestation. For example, Fearnside (1987) discusses the relationship between internationally funded development projects, highway building, immigration, land speculation and deforestation in Brazilian Amazonia. Other studies have assessed the role of government policy and land-tenure conflicts in promoting environmental degradation (e.g. Moran, 1981; Fearnside, 2001). This category also includes local case studies that explore the interaction of social, economic and cultural factors in determining land settlement patterns and agricultural practices (e.g. Schmink & Wood, 1992; Walker *et al*., 1993).

The third category involves conservation gap analyses that assess the impacts of deforestation on different vegetation types. Kangas (1990) assessed the effects of simulated deforestation scenarios on seventeen major vegetation types in Brazilian Amazonia, whereas Fearnside & Ferraz (1995) evaluated the representation of vegetation types within nature reserves in each of the nine states of Brazilian Amazonia. Ferreira (2001) conducted a similar analysis but focused on the distribution of vegetation types within eco-regions defined by major river systems in Brazilian Amazonia.

The final category involves modelling studies that attempt to identify the proximate causes of Amazonian deforestation. Such studies underlay efforts to predict the future condition of Amazon forests and evaluate proposed development schemes in the region (e.g. Carvalho *et al*., 2001; Laurance *et al*., 2001b). Fearnside (1993), for instance, used regression techniques to estimate the proportion of deforestation in Brazilian Amazonia caused by small landowners vs. large-scale cattle ranchers, whereas Imbernon (2000) assessed the effects of rapid population growth on forests in Rondônia. In a preliminary analysis, Wood & Skole (1998) explored the effects of demographic variables (e.g. population density, ranch and farm densities, rural immigration) on deforestation in Brazilian Amazonia. More generally, other investigators have examined the influence of micro- and macroeconomic variables on tropical deforestation (e.g. Reis & Margulis, 1991; Lambin, 1994; Pfaff, 1996; Kaimowitz & Angelsen, 1998).

Although these various studies have provided important insights, much remains unknown regarding the ultimate and proximate causes of Amazonian deforestation. For example, government policies in Brazil promote rapid immigration into the Amazon (Imbernon, 2000; Laurance *et al*., 2001a), but the relative effects of rural vs. urban populations on deforestation are poorly understood. Likewise, new highways and roads sharply increase Amazonian deforestation (Fearnside, 1987; Imbernon, 2000; Carvalho *et al*., 2001; Laurance *et al*., 2001b; Nepstad *et al*., 2001; Steininger *et al*., 2001a), but their impacts on a basin-wide scale have not been rigorously quantified. Finally, biophysical factors such as annual rainfall, dry-season severity, and soil fertility may influence deforestation (Moran, 1981; Fearnside, 1984; Steininger *et al*., 2001a) but have been poorly studied in this context (but see Schneider *et al*., 2000).

In this study, we assess the influence of ten biophysical and anthropogenic predictors on deforestation for the entire Brazilian Amazon. These include human-demographic variables, factors that affect physical accessibility to forests, and parameters that influence land-use suitability for human occupation and agriculture. Our analysis is quantitatively rigorous, incorporates the most recent available information on Amazonian deforestation, and includes potentially important anthropogenic and biophysical variables whose effects have not been evaluated on a basin-wide scale.

METHODS

GIS analyses

Most data processing was carried out at the GIS laboratory of the Biological Dynamics of Forest Fragments Project in Manaus, Brazil, using ArcView 3.2, Spatial Analyst 2.0, and IDRISI (1996a, b) software on a Windows PC. Analyses were conducted at two spatial scales, using quadrats of

2500 km^2 (50 × 50 km) and 400 km^2 (20 × 20 km). Because the patterns were similar, however, only results for the 2500-km^2 quadrats are presented here.

There were 1927 quadrats of 2500-km^2 in the Brazilian Legal Amazon (Fig. 1), a region of 4.0 million km^2 that encompasses all Amazon-basin forests within Brazil and some adjoining woodlands and savannas. The quadrats in our analysis do not include those along the margins of the Legal Amazon that had < 80% of their area within the region's boundaries, which were excluded from analyses. For each quadrat, deforestation and predictor variables were extracted into data tables to permit statistical analysis.

Deforestation

Data on forest cover in the Brazilian Amazon were derived from 1999 imagery produced by the National Oceanographic and Atmospheric Administration using 1992 Pathfinder and 1998 AVHRR satellite data (www.ngdc.noaa.gov/dmsp/fires/brazil/brazil_main.html). Separate georeferenced images for the individual states in the Brazilian Amazon (e.g. Rondônia, Acre) were image-mosaiced using Imagine 8.4 software, and the composite file was georeferenced with a second-order polynomial transformation to digital maps provided by the Brazilian Socio-Environmental Institute [Instituto Socioambiental (ISA), 1999].

The final imagery included four categories of coverage: forest, water, areas of persistent light at night (cities), and non-forested areas (see the website above for the elaborate procedure used to discriminate these four cover-classes). Non-forested areas included both deforested lands and open vegetation (principally *cerrado* savanna and open woodland). To discriminate deforested areas from open vegetation, the latter was converted to raster format and subtracted from the original image using digital vegetation maps (ISA, 1999). In addition, cities and areas flooded by hydroelectric reservoirs (e.g. Balbina & Tucuruí reservoirs) were classified as being deforested. The final result was an image, based on 1-km^2 pixels, in which forested areas, deforested lands and natural bodies of water were discriminated. Per cent deforestation data were calculated by determining the proportion of deforested pixels within each 2500-km^2 quadrat.

Factors affecting accessibility to forests

Highways

Data on existing highways (defined as being paved) were derived from digitized and georeferenced maps from ISA (1999), augmented with extensive personal knowledge of the region. Using IDRISI, the distance to the nearest highway was determined for each 1-km^2 pixel within the Brazilian Amazon, and the mean distance was then calculated for all 2500 pixels in each quadrat. This mean provided an effective index of highway density that also included the potentially important effects of highways in adjoining quadrats.

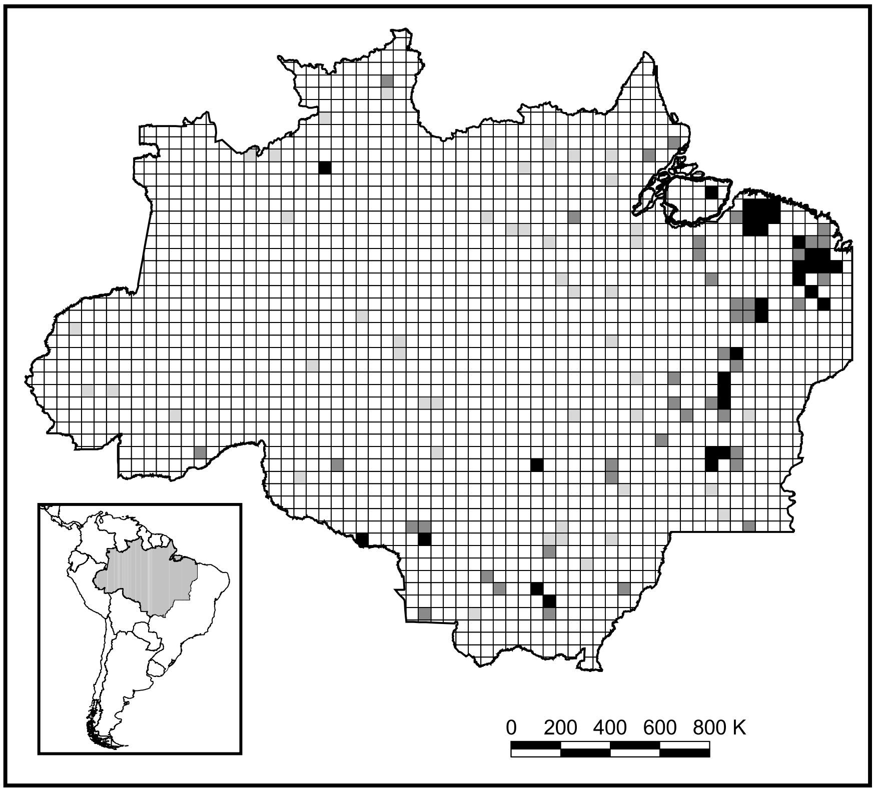

Figure 1 The Brazilian Legal Amazon divided into 2500-km^2 quadrats. The 120 quadrats used in this study are shown in three shades (light grey, 0–33.3% deforested; dark grey, 33.3–66.7% deforested; black, > 66.7% deforested).

Roads
Data on roads (defined as being unpaved) were quantified separately from paved highways, because roads provide less-efficient transportation than highways and may not be usable during the wet season. Data for roads were generated in the same way as those for paved highways, using data from ISA (1999).

Navigable rivers
The distribution of major navigable rivers in the Brazilian Amazon was estimated using georeferenced data from ISA (1999). We excluded from the analysis any rivers of < 1 km in width and any river stretches that were isolated from the main stem of the Amazon or Rio Negro Rivers by cascades or waterfalls. For each quadrat, the distance to the nearest river was calculated for each 1-km^2 pixel and the mean value for all pixels within each quadrat was used to provide an overall index of river accessibility.

Human population density

Urban populations
Data on the population sizes of all legally incorporated Amazonian cities were collected in the 2000 national census by the Brazilian Institute for Geography and Statistics (IBGE) 2000. The data were downloaded as tables (www.ibge.gov.br) and combined with a map of city locations produced by ISA (1999). This coverage was used to determined the size of the urban population within each quadrat (because data on the physical dimensions of each city were not available, the entire population of each city was assigned to the quadrat in which the city centre occurred; although imperfect, this procedure likely yielded few important errors because the quadrats used were relatively large).

Rural populations
Data on rural-population density were also determined using data from the 2000 national census (IBGE, 2000). Information on rural-population sizes were collected for 780 municipalities (which vary considerably in size) within the Brazilian Amazon. These data were converted to population densities for each municipality, at a spatial scale of 1-km^2 pixels. For each quadrat, the rural-population density was the mean value for all pixels within the quadrat.

Climatic factors

Annual rainfall
Data on mean annual rainfall were based on a figure derived from an analysis of 800 simple pluviometric sites in the Brazilian Amazon (Sombroek, 2001). These sites were distributed across the basin but tended to be somewhat concentrated along rivers, where physical access is easier. The rainfall data were used to derive rainfall isoclines at 200–400-mm intervals for the region (Sombroek, 2001), which were digitized using ArcView and georeferenced using IDRISI with twenty control points. To avoid abrupt boundaries between isoclines, rainfall data were interpolated using the TIN (Triangulated Networks and Surface Generation) mode of IDRISI. This yielded a continuous rainfall surface at a spatial scale of 1-km^2 pixels.

Dry-season severity
Data on average duration of the dry season were also produced from the digitized map derived from Sombroek (2001), who generated isoclines of the number of months with < 100-mm rainfall. Again, to avoid abrupt boundaries between isoclines, data were interpolated using the TIN mode of IDRISI, yielding a continuous surface of dry-season severity at a scale of 1-km^2 pixels.

Soil factors

Data on soils were based on a 1 : 3,000,000-scale digital soil map of Brazilian Amazonia that was produced in the 1970s by the Soils Division of the Brazilian Institute for Agricultural Research (EMBRAPA, Rio de Janeiro), which is regarded as the best available soils map for the Amazon (W. G. Sombroek, pers. comm.). The map contains seventeen major soil types that are further subdivided into over 100 subtypes, using the Brazilian soil taxonomy (cf. Beinroth, 1975). The map was used to generate data layers for three indices of soil suitability for agriculture: (1) a general index of soil fertility (see below), (2) waterlogging and hydromorphy, and (3) soil shallowness/stoniness. Information for classifying the different soil subtypes was derived from published sources (especially Sombroek, 1984, 2000; Oliveira *et al*., 1992).

Soil fertility
This parameter is a composite index of soil suitability for agriculture that ranges from 1 (poorest soils) to 10 (best soils), and that incorporates data on soil chemistry, texture, depth, waterlogging, stoniness, and other features. Soil-fertility classes 8–10 have the highest agricultural potential. These include alluvial soils in *várzea* forests (seasonally inundated by whitewater rivers that carry nutrient-rich sediments from the Andes Mountains), *terra roxa* soils (nutrient-rich, well-structured upland soils that have formed on base-rich rock and are in high demand for cocoa and other nutrient-demanding crops), eutrophic Cambisols (young, relatively unweathered soils with high-activity clay and high nutrient status), and Vertisols (clay soils with high-activity clay minerals and high nutrient contents). All of these soil types have very limited distributions, collectively encompassing just 1.8% of the Brazilian Amazon, according to the EMBRAPA map.

Soil classes 5–7 have some agricultural potential but also important limitations, such as high acidity, low nutrient availability, shallowness, waterlogging, and concretionary soils. These soil types are very extensive, comprising 53.4% of the Brazilian Amazon according to the EMBRAPA map.

Soil classes 2–4 have restricted potential for certain low-demand uses, such as cattle pasture or undemanding tree crops. These include the intensively weathered Xanthic Ferralsols of central Amazonia, very stony and shallow soils, nutrient-poor waterlogged soils and Plinthosols (soils that form into hardened laterite when exposed to wetting and drying cycles). According to the EMBRAPA map, these soils encompass 34.8% of the Brazilian Amazon.

Soil class 1 has no potential for agriculture. These include very sandy soils (podzols and quartz sands, some of which are waterlogged) and a small area of salt-affected soils along the ocean shore. This class encompasses 7.8% of the Brazilian Amazon, according to the EMBRAPA map.

Soil waterlogging

This index quantifies waterlogging, poor drainage and flooding risk, and has four classes. A value of 0 indicates soils with no waterlogging or flooding (77.9% of the Brazilian Amazon). Soils with a value of 1 are at risk of seasonal flooding but are not hydromorphic (anoxic), such as *várzea* soils (0.7% of the Brazilian Amazon). A value of 2 indicates soils that are hydromorphic at greater depth or periodically waterlogged (4.6% of the Brazilian Amazon), whereas 3 indicates soils that are hydromorphic near the soil surface and often permanently waterlogged (such as gley soils; 14.6% of the Brazilian Amazon).

Soil shallowness and stoniness

This index has three classes: 0 (not shallow or stony; 91.5% of the Brazilian Amazon), 1 (somewhat shallow or stony, including relatively young soils in mountainous regions and concetionary soils; 1.9% of the Brazilian Amazon), and 2 (very shallow or stony soils, including very young soils in mountain regions and a small area of Planosols that have a compact subsoil; 4.4% of the Brazilian Amazon). This index is important because certain young soils are chemically rich but too shallow for agricultural uses and have low water-holding capacity.

Statistical analysis

Predictors describing rural and urban populations, and distances to paved highways, roads, and navigable rivers were log-transformed to improve normality and the linear fit to deforestation data, whereas per cent-deforestation data were arcsine-squareroot transformed to improve normality. To minimize spatial autocorrelation among the 1927 quadrats, a random subset of 120 quadrats was selected for statistical analysis. To ensure that a wide range of deforestation values were included, chosen quadrats were stratified on deforestation intensity by randomly selecting forty plots within each of three deforestation categories (0–33.33, 33.33–66.67 and > 66.67% deforestation).

Because many of the predictor variables were strongly intercorrelated, a robust ordination method, non-metric multidimensional scaling (NMDS), was used to identify key orthogonal (statistically independent) gradients in the data set (McCune & Mefford, 1997). The number of ordination axes was determined by examining the relationship between stress (unexplained variance) and number of axes, and by using randomization tests to confirm that each axis in the final analysis explained significantly more variation than expected by chance. All variables were standardized before analysis with the relativization by maximum method (Noy-Meir *et al.*, 1975), and Sorensen's distance metric was used to generate dissimilarity matrices.

Following the ordination, best-subsets and multiple linear regressions were used to test the efficacy of the ordination axes as predictors of deforestation. Performance of the final regression model was assessed by comparing the standardized residuals to both the fitted values and to each significant predictor (Crawley, 1993). Simple product–moment correlations among the transformed variables, using Bonferroni-corrected *P*-values to minimize type II statistical errors, were also used to assess the environmental correlates of deforestation.

RESULTS

Among the 120 randomly selected quadrats (Fig. 1), the ordination revealed two major axes of variation (Table 1). Both axes explained significantly more variation than expected by chance ($P = 0.02$ in both cases, randomization tests). Axis 1, which captured 62.0% of the total variation, mainly discriminated among areas with dense rural and urban populations and many highways, and those with sparse populations and no highways. Axis 2 captured 26.4% of the total variation, and described a gradient between sites with low dry-season severity, many navigable rivers, and few unpaved roads, and those with opposite values.

Best-subsets and multiple regression analysis revealed that both axes were highly significant predictors of deforestation ($F_{2,117} = 85.46$, $P < 0.0001$), collectively explaining 59.4% of the total variation in forest destruction. Both axes were negatively associated with deforestation,

Table 1 Product–moment correlations of ten predictor variables with two ordination axes produced by non-metric multidimensional scaling

Variable	Axis 1	Axis 2
Rural-population density	−0.881*	−0.130
Urban-population size	−0.904*	−0.180
Distance to nearest paved highway	0.791*	0.424*
Distance to nearest unpaved road	0.355*	0.579*
Distance to nearest navigable river	0.377*	−0.740*
Annual rainfall	0.069	0.782*
Dry-season severity	−0.381*	−0.769*
Soil fertility	0.301*	0.284*
Soil waterlogging	−0.440*	0.290*
Soil depth and stoniness	0.396*	−0.129
Variation explained†	62.0%	26.4%

*Significant correlations, using a Bonferroni-corrected α-value ($P = 0.0025$).

†Coefficients of determination for correlations between ordination distances and distances in the original *n*-dimensional space.

indicating that forest loss increased near highways and roads, in areas with larger rural and urban populations, and in drier areas with stronger dry seasons. Of the two ordination axes, axis 1 was more important, individually explaining 53.6% of the variation in deforestation ($F_{1,118} = 136.38$, $P < 0.0001$), whereas axis 2 individually explained only 9.6% of the variation ($F_{1,118} = 12.57$, $P = 0.0006$). This result suggests that highways and human population density were the main determinants of local deforestation, with rainfall and unpaved roads influencing deforestation to a lesser degree.

The efficacy of the ten predictors was further assessed using product–moment correlations with a Bonferroni-corrected α-value ($P = 0.005$). The two strongest correlates of deforestation were distance to paved highways ($r = -0.759$) and rural-population density ($r = 0.731$), followed by urban-population size ($r = 0.656$), dry-season severity ($r = 0.443$) and distance to unpaved roads ($r = -0.355$) ($P < 0.001$ in all cases). Soil stoniness/shallowness also had a weaker but significantly negative effect on deforestation ($r = -0.254$, $P = 0.005$). These analyses were concordant with the regression models and suggest that highways and human population density are the strongest predictors of local deforestation in the Brazilian Amazon. Deforestation is also associated with increasing dry-season severity, more roads, and deeper and less-stony soils.

The key predictors often had nonlinear relationships with deforestation, especially when the predictors varied over several orders of magnitude. These relationships were examined in detail by plotting each variable against deforestation using all 1927 quadrats within the Brazilian Amazon. On average, deforestation rose mostly sharply within 50–100 km of paved highways (Fig. 2) and within 25–50 km of unpaved roads (Fig. 3). The relationship between deforestation and rural-population density was also nonlinear, tending to plateau beyond 100 persons km^{-2} (Fig. 4). Dry-season severity, however, tended to have a roughly linear relationship with deforestation (Fig. 5).

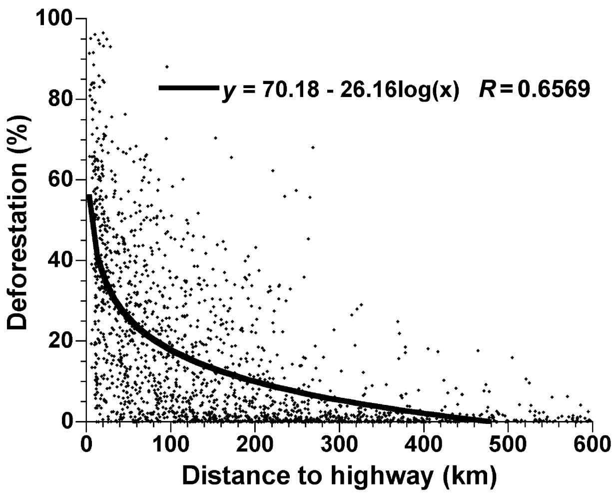

Figure 2 Relationship between deforestation and the mean distance to paved highways in the Brazilian Legal Amazon. Data for quadrats further than 600 km from highways are not shown.

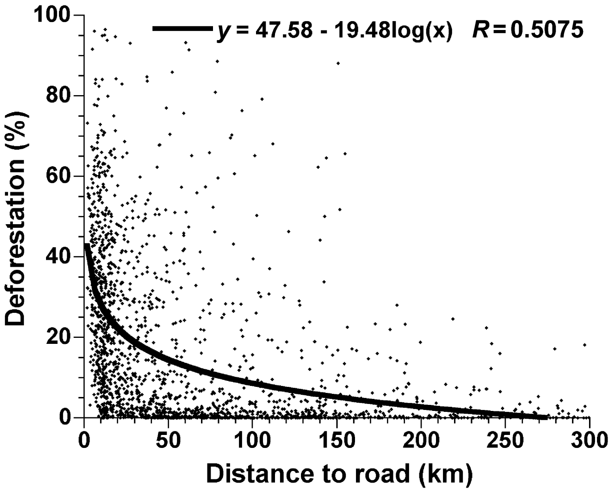

Figure 3 Relationship between deforestation and the mean distance to unpaved roads in Brazilian Amazonia. Data for quadrats further than 300 km from roads are not shown.

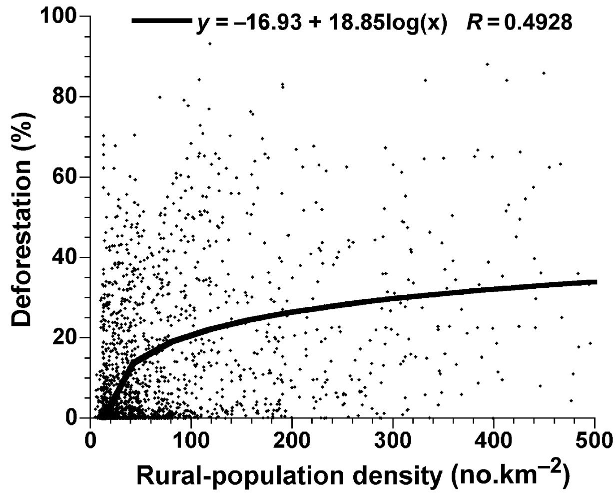

Figure 4 Relationship between deforestation and rural-population density in Brazilian Amazonia. Data for rural densities above 500 persons km^{-2} are not shown.

DISCUSSION

Study limitations

It is important to emphasize that our findings do not appear to be strongly influenced by the spatial scale of our analysis. When we performed a finer-scale analysis (by dividing the Brazilian Amazon into over 8000 quadrats of 20 × 20 km, and then randomly selecting 300 quadrats, stratified on

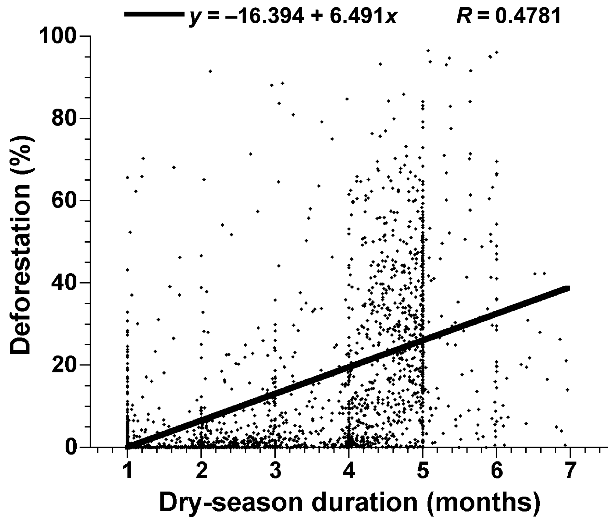

Figure 5 Relationship between dry-season duration (number of months with < 100 mm of rainfall) and deforestation in Brazilian Amazonia.

deforestation intensity, for statistical analysis) the results were broadly similar to those presented here. The only notable difference is that in the fine-scale analysis, highways and roads emerged as the two strongest correlates of deforestation, followed in importance by climatic factors (annual rainfall and dry-season intensity) and rural-population density. As before, soil factors seemingly had little influence on deforestation activity.

The validity of our conclusions obviously depends upon the quality of available spatial data for Brazilian Amazonia. Data on demographic variables, human infrastructure, rivers and deforestation were recently collected and probably quite accurate, but spatial data on soils (see below) and climatic variables were based on large-scale interpolations by investigators who relied on a relatively modest number of sampling points, given the vastness of the study area. In all cases, however, we used the most reliable information available to us, and we believe that the broad-scale trends we identified are generally reliable.

Another limitation of this study is that spatial autocorrelation among selected quadrats was not eliminated entirely, despite being substantially reduced. This occurred because deforestation in Brazilian Amazonia is concentrated in certain areas (Skole & Tucker, 1993; Alves *et al*., 1999), so that quadrats with the highest deforestation (> 66.7% forest loss) tend to be clustered together (Fig. 1). An alternative strategy is to select quadrats purely at random, rather than stratifying on deforestation intensity, but this would result in a skewed distribution of deforestation values (with most quadrats having little or no deforestation, and a limited number having much higher deforestation). In this study, we tolerated some spatial autocorrelation to ensure that sampled sites included a wide range of deforestation values.

Finally, many of the predictors we assessed were both spatially autocorrelated (e.g. population density, highways and roads) and functionally related (e.g. highways promote forest colonization, leading to local population increases), and thus it is difficult to assess the impacts of such factors independently. Moreover, the causal relationships between the predictors and deforestation are sometimes complex. For example, roads clearly promote deforestation, but deforestation can also promote roads by providing political justification for road-building, thereby forming a positive feedback loop (see Fearnside, 1987). Further studies that stratify sampling on each predictor, focus on subsets of the basin to reduce correlations among variables, and incorporate time-lags and path analyses will be needed to reveal more fully the functional relationships among these predictors and deforestation.

Highways, roads and rivers

Few would be surprised to learn that highways and roads sharply increase Amazonian deforestation (Fearnside, 1987; Imbernon, 2000; Carvalho *et al*., 2001; Laurance *et al*., 2001b; Nepstad *et al*., 2001; Steininger *et al*., 2001a). Our analysis, however, helps to quantify the impacts of roads and highways on a basin-wide scale, and to evaluate their importance relative to other potential predictors. In this study, highway proximity emerged as the single most important predictor of deforestation. Because they promote efficient, year-round access to forests, highways tend to have considerably larger-scale impacts than roads (compare Figs 2 & 3). It must be noted, however, that major highways tend to spawn secondary road networks, as has occurred extensively in the southern and eastern Amazon (for example, around the Belém-Brasília, TransAmazon, and BR-364 highways). Thus, the effects of highways and roads cannot be assessed completely independently.

An unexpected result is that distance to navigable rivers was not a significant predictor of deforestation. It is important to emphasize, however, that our analysis focuses on identifying general, basin-wide predictors. Significant deforestation has obviously occurred along some major rivers (especially whitewater rivers such as the Solimões and Amazon, which carry relatively fertile sediments), but this is minor compared with the vast areas of deforestation associated with highways and roads.

Climate

Another key conclusion of our study is that deforestation was most concentrated in drier, more seasonal areas of the Brazilian Amazon. In Bolivian Amazonia, Steininger *et al*. (2001a) also found that drier, more deciduous forests were most vulnerable to deforestation. The most obvious reason for this pattern is that drier forests are easier to burn, reducing the effort needed to clear forests and maintain pastures and croplands. There might also be some tendency for drier forests to overlay more fertile soils, because heavy rainfall can leach soil nutrients. On a basin-wide scale, our soil-fertility index was weakly but significantly related to annual rainfall ($R^2 = 1.2\%$, $F_{1,1925} = 22.87$, $P < 0.0001$, slope negative; linear regression analysis).

It must be emphasized, however, that the effects of rainfall are complicated by other factors. In Brazilian Amazonia, drier forests are most extensive along the south-eastern margin of the basin, which is also most accessible to immigrants and markets from southern population centres. However, deforestation has also been very high in areas such as Roraima state, which contains extensive seasonal forests but is located in northern Amazonia far from major population centres. In a recent study, Schneider *et al.* (2000) asserted that rainfall, rather than proximity to population centres, is the more important determinant of deforestation in the Brazilian Amazon.

Because deforestation is greatest in seasonal areas, the vulnerability of different Amazonian habitat types is not uniform. Deciduous and semi-deciduous forests, woody oligotrophic vegetation such as *campina* and *campinarana*, regenerating forests, and ecotonal forests at the rain forest-*cerrado* woodland boundary are likely to be most vulnerable (Kangas, 1990; Fearnside & Ferraz, 1995). These forest types have suffered the heaviest deforestation and are poorly represented in parks and reserves (Fearnside & Ferraz, 1995; Ferreira, 2001).

The destruction of Amazonian forests is a major source of atmospheric carbon emissions (Fearnside, 1997; Houghton *et al.*, 2000). The high vulnerability of drier forests could influence carbon emissions, because seasonal forests have lower above-ground biomass than wetter forests (Houghton *et al.*, 2000). However, drier forests probably contain more below-ground biomass, because they require extensive root systems to access deep soil water (Nepstad *et al.*, 1994). As a result, the destruction of seasonal forests in Amazonia could ultimately produce nearly as much atmospheric carbon emissions per hectare as the loss of dense rain forest.

Soils

Among our most surprising results was the seemingly weak effect of soils on deforestation; soil fertility and waterlogging had non-significant effects, and soil depth was of only limited importance. In part, this might reflect limited knowledge about the spatial distribution of Amazonian soils. The soil map we used is regarded as the best available, but is coarse-scale and undoubtedly incomplete. Amazonian soils can be patchy at a spatial scale of hundreds of metres (Moran, 1981; Fearnside, 1984; Chauvel *et al.*, 1987; Laurance *et al.*, 1999), limiting the effectiveness of coarse-scale soil maps. It is difficult, moreover, to create a general index of soil fertility because different crops have varying soil requirements (e.g. stoniness is no problem for pastures and many tree crops but it is for annual crops, whereas waterlogging precludes most crops but is suitable for rice). Finally, soil-texture data were not consistently available to us and certain soil types (e.g. Ferralsols, Acrisols) can include a wide range of different texture classes that substantially affect their agricultural potential.

Despite these limitations, it is quite possible that soils have played a relatively insignificant role in determining deforestation activity on a basin-wide scale. In Brazilian Amazonia, most large-scale colonization and development projects have been implemented with little or no information about soil characteristics (Moran, 1981; Fearnside, 1984). Even on a local scale, soil quality was found to be much less important than distance from roads in determining deforestation by colonists (Fearnside, 1986; Maki *et al.*, 2001). Rather than determining where deforestation occurs, soil features may influence how quickly land is abandoned after being deforested, and how rapidly forest regenerates after abandonment (Saldarriaga *et al.*, 1986; Laurance *et al.*, 1999). It is also not inconceivable that farmers and ranchers on low-fertility soils are forced to clear larger areas of forest than those on better soils, in order to remain viable; this would complicate a simple relationship between soil fertility and deforestation.

Population density

This study clearly implicates local population density as a key correlate of deforestation (see also Wood & Skole, 1998; Imbernon, 2000; Steininger *et al.*, 2001a). Our analyses suggest that rural-population density is a somewhat better predictor of local deforestation than urban-population size, which accords with some earlier analyses (Wood & Skole, 1998; Laurance *et al.*, 2001a). Nevertheless, rural and urban populations in Amazonia interact in complex ways, with frequent movements of people and materials between the two (Browder & Godfrey, 1997; Imbernon, 2000). Although rural populations have the most direct impact on forests, urban populations influence demand for forest resources, market availability, human migration and other factors (Browder & Godfrey, 1997).

In Brazilian Amazonia, not all segments of the rural population are equally important drivers of deforestation. Large-scale cattle ranchers, rather than small-scale farmers, appear to be responsible for well over half of all forest loss (Fearnside, 1993; Wood & Skole, 1998; Nepstad *et al.*, 1999b). However, small-scale farmers and government-sponsored forest-colonization projects have caused extensive deforestation in some areas (Schmink & Wood, 1992; Alves *et al.*, 1999; Imbernon, 2000), and forest exploitation on small farms is often relatively intensive (Fearnside, 1993). Mounting social pressures for agrarian reform, which involves redistributing lands from large to small landowners, could lead to further deforestation at the hands of small-scale farmers (Fearnside, 2001).

Notably, the relationship between rural-population density and deforestation was clearly nonlinear (Fig. 4). The form of this relationship suggests that the initial settlers moving into the frontier have a greater impact on forests than do additional setters arriving later, a result that accords with that of Pfaff (1996). An important implication of this result is that even limited rural populations may have relatively large impacts on forests.

Implications

Our results highlight the critical role of highways, roads and population growth in determining local forest destruction. Clearly, the rapid expansion of the Amazonian population, which rose from about 2.5 million in 1960 to over 20 million today (IBGE, 2000), is increasing pressures on forests. Such dramatic growth has largely resulted from government policies designed to accelerate immigration and economic development in the region, including large-scale colonization schemes, credit and tax incentives to attract private capital, and major transportation projects such as the TransAmazon and Manaus-Boa Vista Highways (Moran, 1981; Smith, 1982; Fearnside, 1987). As a result, the Amazon has the highest rate of immigration of any region in Brazil, and has often been characterized as an 'escape valve' for reducing overcrowding, social tensions and displacement of agricultural workers in other parts of the country (Anonymous, 2001). In addition to rapid immigration, existing populations in the region are growing quickly because most residents begin bearing children at a relatively young age and the population is strongly skewed towards young individuals currently in or entering their reproductive years (Brown & Pearce, 1994; Wood & Perz, 1996).

As part of its policies to promote immigration and rapid economic development, the Brazilian federal government is planning to expand sharply the existing network of paved highways and infrastructure within Brazilian Amazonia. Under the auspices of its *Avança Brazil* (Advance Brazil) programme, the government intends to invest over US$ 40 billion in highways, railroads, gas lines, power lines, hydroelectric reservoirs and river-channelization projects that will criss-cross large expanses of the basin, greatly increasing accessibility to remote frontier areas. About 7500 km of highways will be paved (Laurance *et al*., 2001a) and road networks will also be expanded markedly. In the past, such projects have frequently initiated waves of spontaneous colonization, logging, hunting and land speculation that have dramatically increased forest loss and degradation (Fearnside, 1987, 1990, 2001; Laurance, 1998; Alves *et al*., 1999; Imbernon, 2000; Steininger *et al*., 2001a, b). Although environmental protection in Amazonia has begun to improve (Nepstad *et al*. 2002), the government's capacity to control illegal deforestation, logging, mining and other activities across the vast frontier is still seriously inadequate (Laurance *et al*., 2001a; Laurance & Fearnside 2002).

Modelling studies suggest that the constellation of planned highway and infrastructure projects would dramatically accelerate Amazonian forest loss and fragmentation (Carvalho *et al*., 2001; Laurance *et al*., 2001b). The prospect that remaining forest tracts could be fragmented on a large spatial scale is perhaps the most alarming trend in the Amazon today. Habitat fragmentation affects the ecology of Amazonian forests in myriad ways, such as altering the diversity and composition of fragment biotas, and disrupting ecological processes such as pollination, seed germination and carbon cycling (Lovejoy *et al*., 1986; Skole & Tucker, 1993; Laurance *et al*., 1997, 1998, 2000). Most important of all, fragmented forests become far more vulnerable than intact forests to wildfires (Cochrane & Laurance, 2002), predatory logging (Nepstad *et al*., 1999a), overhunting (Peres, 2001) and other degrading activities. Such changes can interact additively or synergistically, sharply magnifying the overall impact on forests (Laurance & Cochrane, 2001).

It is vital to emphasize, however, that the potentially dire losses of Amazonian forests projected by recent studies (Carvalho *et al*., 2001; Laurance *et al*., 2001b) are not yet a *faite accompli*. Pressures from the international community and from foreign investors (which provide significant financial support for *Avança Brazil* and other Amazonian development initiatives) can strongly influence development policy, planning and environmental assessment in Brazil. Cooperative resource-management programmes supported by wealthy nations (e.g. Anonymous, 1999a) and non-governmental organizations (e.g. Anon, 1999b) can also have major environmental benefits. Such efforts are crucially needed to ensure that Amazonian forests are not irreversibly degraded in the coming decades.

ACKNOWLEDGMENTS

We thank Bill Magnusson, Jeff Chambers, Mark Cochrane, Don Drake, Dave Towns, and an anonymous referee for commenting on drafts of the manuscript. Support was provided by the NASA-LBA programme, A. W. Mellon Foundation, Conservation International, National Institute for Amazonian Research (INPA), and Smithsonian Tropical Research Institute. This is publication number 368 in the BDFFP technical series.

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