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The future of deforestation in the Brazilian Amazon

Kathryn R. Kirby[a], William F. Laurance[b,*], Ana K. Albernaz[c], Götz Schroth[d], Philip M. Fearnside[e], Scott Bergen[f], Eduardo M. Venticinque[g], Carlos da Costa[g]

[a]*Department of Biology, McGill University, Montreal, Canada*
[b]*Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Panamá, Republic of Panamá*
[c]*Museu Goeldi, Belém, Brazil*
[d]*Conservation International 1919 M Street, Washington, D.C. 20036, USA*
[e]*Department of Ecology, National Institute for Amazonian Research (INPA), Manaus, Brazil*
[f]*Centre for the Environment, Mt Holyoke College, South Hadley, USA*
[g]*Biological Dynamics of Forest Fragments Project, National Institute for Amazonian Research (INPA), Manaus, Brazil*

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Abstract

Concern about the future of Amazonian forests is growing as both the extent and rate of primary forest destruction increase. We combine spatial information on various biophysical, demographic and infrastructural factors in the Brazilian Amazon with satellite data on deforestation to evaluate the relative importance of each factor to deforestation in the region. We assess the sensitivity of results to alternative sampling methodologies, and compare our results to those of previous empirical studies of Amazonian deforestation. Our findings, in concert with those of previous studies, send a clear message to planners: both paved and unpaved roads are key drivers of the deforestation process. Proximity to previous clearings, high population densities, low annual rainfall, and long dry seasons also increase the likelihood that a site will be deforested; however, roads are consistently important and are the factors most amenable to policymaking. We argue that there is ample evidence to justify a fundamental change in current Amazonian development priorities if additional large-scale losses of forests and environmental services are to be avoided.
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* Corresponding author.
E-mail address: laurancew@si.edu (W.F. Laurance).

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1. Introduction

Almost 70% of the Amazon basin falls within Brazil's borders and the country sustains 40% of the world's remaining tropical rain forests. Within Brazil, the 'Legal Amazon'[1] region covers 58% of the national territory and shares borders with all eight other Amazonian countries: Bolivia, Peru, Ecuador, Columbia, Venezuela, Guyana, Suriname and French Guiana. The region's geopolitical position, size and low population density have meant that it has long been seen as 'strategically vulnerable and economically underutilized' by Brazil's federal planners [12]. Indeed, the Legal Amazon still houses only 11% of Brazil's population, and in 1999 it contributed just 4% of the country's GDP [12]. However, the forests of the Amazon basin also provide environmental services that are important both locally and globally including the conservation of biodiversity, carbon storage, and the regulation of regional hydrological cycles, among others [21]. Concern about the future of Amazonian forests is growing as both the total extent and rate of primary-forest destruction increase (Fig. 1).

Several recent studies of land-use change in the Brazilian Amazon have used empirical methods to describe the relationships among deforestation and its 'driver' variables, be they biophysical, infrastructural or demographic factors. Although our growing understanding of these relationships could inform policy and decision-making processes, federal-level planning for the Amazon region continues to emphasize projects that will maximize foreign earnings through benefits to export-oriented industries, with little regard to the impacts of planned projects on the forest landscape. In this paper, we first describe the historical development policies and land uses that have contributed to deforestation in the Brazilian Amazon. We then present the findings of a new, spatially explicit analysis of the predictors of Amazonian deforestation and compare these findings to previous empirical studies of Amazonian deforestation. Finally, in light of current trends in factors that have been shown to be strongly related to forest clearing, we discuss the future of deforestation in the region.

2. Historical development trends in the Brazilian Amazon

Approximately 4 million km^2 of the 5 million km^2 Legal Amazon region of Brazil were forested at the beginning of the 20th century, with the remaining areas covered by naturally occurring savannah shrub lands (*cerrado*) and savannah grasslands (*campos naturais*). Prior to the early 1960s, access to the Amazon was severely restricted and aside from limited clearing along rivers the forest remained essentially intact. Construction of the first road through the region, the Belém–Brasilía highway, began in 1958 with the goal of integrating western and northern states with the rest of the country [53]. The initiation of the Cuiabá–Porto Velho (BR-364) highway followed in 1968 to provide access to the southern portion of the Amazon. These first two highways—the only federal highways in

[1] The 'Legal Amazon' includes the states of Amapá, Amazonas, Rondônia, Roraima, Pará, Maranhão (west of 44°W), Tocantins, Goiás (north of 13°S), and Mato Grosso.

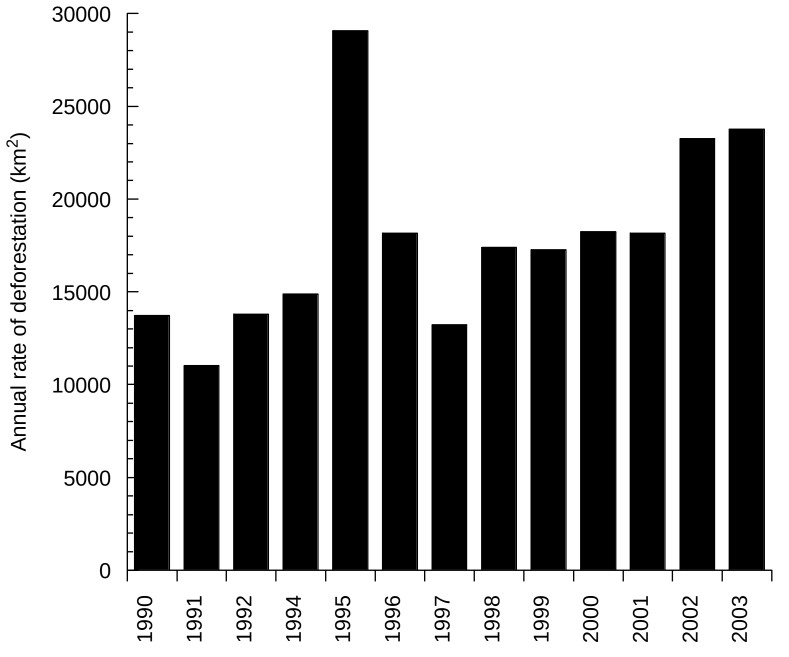

Fig. 1. Annual rates of deforestation in the Legal Amazon from 1990 to 2003. Deforestation was not measured in 1993, and the mean annual rate of change from August 1992–August 1994 is, therefore, presented for the 1994 year.

the Legal Amazon to be paved and, therefore, passable year-round before the late 1990s—are at the heart of the ‘arc of deforestation’, which to date is the focal region of deforestation in the Brazilian Amazon [44,56] (Fig. 2). Several other mostly unpaved highways that have been important in the historical deforestation of the Amazon include the Transamazon (BR-230), which runs west to east from Lábrea through Marabá, the BR-163, which runs south to north from Cuiabá to Santarém, and the BR-174, which runs south to north from Manaus through Boa Vista (Fig. 2).

In addition improving transport infrastructure, the government used various incentives to encourage colonization and the development of intensive economic activities in the region throughout the 1964–1985 military dictatorship period [12]. These incentives were overwhelmingly directed at extensive cattle ranching projects (631 of 950 projects approved for funding between 1966 and 1985) [31]. Large-scale mining, timber extraction and hydroelectric energy projects were also undertaken. In focusing on intensive economic activities, the government proposed to produce revenues that would service Brazil’s foreign debt and finance further development [12]. Aside from a few localized government-settlement programs (particularly along the Transamazon highway in the early 1970s and in the state of Rondônia from the mid-1970s onwards [19]), colonization was generally unorganized and was expected to occur on its own around large projects [12]. In the case of the Belém-Brasilía highway, two million people settled along the highway in its first 20 years, mainly in the state of Pará [53].

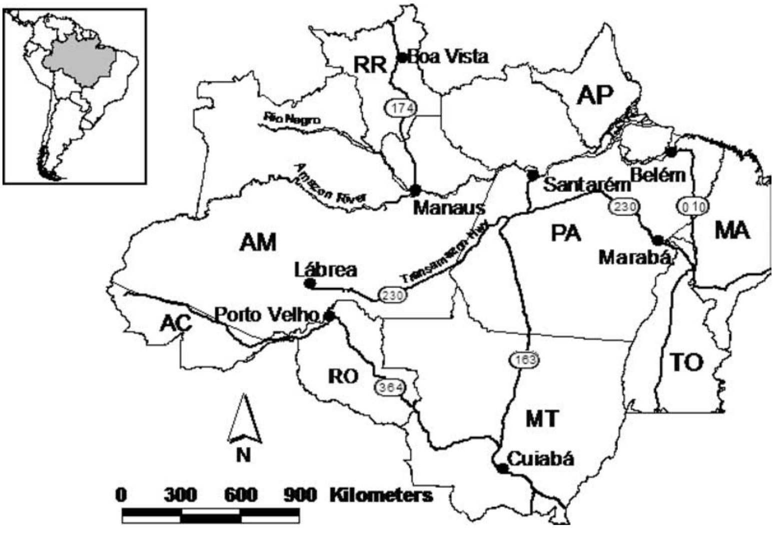

Fig. 2. Boundaries of the Legal Amazon and its states (AC, Acre; AM, Amazônas; AP, Amapá; MA, Maranhão; MT, Mato Grosso; PA, Pará; RO, Rondônia; RR, Roraima; TO, Tocantins), and cities and highways mentioned in the text.

Calls for the conservation of Brazil's rainforests began to emerge in the mid-1970s with the publication of the first estimates of the extent of Amazonian deforestation. By the late 1980s, international interest in the conservation of the Amazon had begun to affect Brazil's ability to attract foreign investment and financial support for large projects [53,41]. The Brazilian government's increasing preoccupation with its environmental image is reflected in its Amazonian policy beginning in 1985. Incentives to cattle ranchers were formally withdrawn through a series of decisions and decrees in 1985, 1989, and 1991[2] [20,41,53]. In 1988, as part of the new constitution, the destruction of Amazon and Atlantic rainforests became a crime under the penal code, although little attention was given to the enforcement of these laws [20]. In 1989, Brazil volunteered to host the 1992 UN Conference on Environment and Development (UNCED), and in 1993 the Pilot Program to Conserve the Brazilian Rainforest (PP-G7) was launched by the Group of Seven industrialized countries (Canada, France, Germany, Italy, Japan, United Kingdom, United States of America) in cooperation with Brazil. Germany was the largest contributor to the PP-G7's budget of $340 million, which was to finance such initiatives as the demarcation of indigenous territories and extractive reserves, the strengthening of environmental institutions and local governments, and NGO demonstration projects [52].

The launch of the PP-G7 coincided with the general recession of the late 1980s that alone reduced development initiatives and, therefore, deforestation throughout Brazil [20,53]. President Fernando Collor de Melo, who had led the charge to present a positive

[2] Though see Fearnside [25]: 'contrary to popular belief, many ranchers still receive fiscal incentives because the June 25, 1991 decree (no. 153) on incentives only suspended granting new incentives, rather than revoking old (already approved) ones'.

environmental image of Brazil, resigned in late 1992 under threat of impeachment for corruption [41]. Following the UNCED Rio Summit, Amazonia disappeared from both the international and Brazilian press, and Brazil's politics began to shift back toward promoting the interests of military, mining, construction and agricultural groups. Nationalist sentiments also contributed to this shift [41].

3. Land use and deforestation

In terms of land-use activities, cattle ranching and small-scale farming have historically played the most significant role in the clearing of Amazonian forest. In addition, the importance of soy farming as a land-demanding economic activity has grown dramatically in the last ten years [24,61]. Each of these activities tends to be strongly associated with agricultural establishments of particular sizes; data from the most recent national agricultural census reveal both the highly unequal distribution of land in the legal Amazon and the disproportionate contribution of cattle ranching and soy farming to deforestation (Table 1). For example, properties greater than 2000 ha in size, which tend to be cattle ranches or soy farms, constitute only 1% of all agricultural establishments in the nine Amazonian states but control 46.8% of all land converted from forest or *cerrado* to agriculture. In contrast, subsistence farms of less than 20 ha constitute over 50% of establishments in Amazonia but control only 1.5% of land converted to agriculture [14].

The historical role of cattle ranching in Amazonian deforestation is partly a result of the favourable incentives received by cattle ranchers throughout the 1965–1985 period. Economic analyses have shown that where credit was available, converting forest to pasture was more profitable than the sustainable use of already-cleared lands [34,53]. However, even at the height of the government-incentives programs in 1975, over 45% of clearing along the Belém-Brasilía highway was in agricultural establishments—almost all large ranches—that received no government subsidies [19]. In part, this reflects the attractiveness of cattle ranching to Amazonian farmers: cattle are a highly liquid investment that can be readily sold if necessary; there are strong local markets for beef

Table 1
Size of agricultural establishments in the nine Amazonian states and their principal agricultural products based on Brazil's 1995/1996 agricultural census

Size of establishment	Percent of all establishments	Percent of all land converted from forest or cerrado to agriculture controlled by establishments of this size	Principal agricultural products
<20 ha	54	2	Subsistence (manioc, rice)
20–100 ha	28	Not available	Subsistence, some cash products (manioc, bananas, milk)
100–2000 ha	15	Not available	Cattle, soybean
>2000 ha	1	47	Cattle, soybean

Note that 2% of establishments could not be classified from the census data [37,14].

throughout Brazil; cattle can be brought to the market on foot, and therefore, do not require truck-grade roads; sales of cattle can be delayed without incurring major losses; cattle ranching is not labour-intensive; cattle produce milk, skins, manure, offspring and meat and are less vulnerable to annual variation in weather than crops; and cattle ranching has traditionally been regarded as a prestigious activity in Brazilian society [2,19,51].

Today Brazil's cattle herd is the largest in the world [61]. However, numerous studies have emphasized that large landholders in Amazonia are generally less interested in raising cattle than in securing their land tenure. Under Brazilian legislation, clearing land for pasture is considered an 'effective use' of land and is a first step towards securing land ownership [33]. Securing ownership is critical to both land speculators and large landholders because of the threats of invasion by landless peasants or of expropriation by a land-redistribution program. Cleared land is also worth 5–10 times more than forested land, and clearing is, therefore, well worthwhile to the owner whose ultimate goal is resale [51]. The strong performance of land prices in the face of Brazil's high rates of inflation in the 1970s and 1980s and the fact that capital-gains taxes are almost never collected has meant that land speculation has long been popular in Amazonia [25,53]. The cheapest and most efficient way of maintaining cleared land is by cattle grazing, and the ubiquity of cattle operations with very low stocking densities in Amazonia suggests that maintaining land cleared is indeed a prime motivation for much of the cattle ranching in the region [51,66].

After cattle ranchers, small farmers have played the most significant role in the clearing of Amazonian forest. Most of the original small-farmer immigrants to Amazonia came from drought-stricken northeastern states or from south-central Brazil where increasing industrialization of farming was leading to land concentration and to the expulsion of small-holders to new frontiers. In the Amazon, the initial land claim by small farmers is accompanied by farm creation using slash and burn. The extent and rate of clearing are determined by labour supply and capital, and the process of farm establishment may span a decade or more [18,68]. The average small farmer in Amazonia clears 1 ha of forest per year [35]. A plot can generally support annual crops for 2–3 years, after which soils are exhausted and new areas cleared. Old fields are left fallow or converted to pasture. In view of the expense of fertilizers, the shortage of labour in Amazonia, and the abundance of inexpensive forestland, several studies have argued that slash-and-burn is by far the most economical means for farmers to improve the fertility of the soils [19,55]. Unfortunately, the fallow periods are rarely long enough to allow soils to recuperate fully, and the system is, therefore, not sustainable [19].

More recently, a long growing season, the development of new cultivars, ample agricultural financing and cheap land prices have fostered the rapid expansion of the soy industry in Brazil. The country is currently the second-largest global producer of soybeans after the United States. Historically, soy producers have been concentrated in southern and central Brazil and in savannah areas of the Legal Amazon. However, as prices for soybeans continue to rise, soy producers are pushing northwards into forested areas of the Amazon, particularly along the recently paved portions of the Cuiabá-Santarém (BR-163) highway [24,61]. Soy farmers generally buy already-cleared land from small farmers, displacing the small holders to cities or to new frontiers; in the latter case, the process of farm establishment is reinitiated [10]. Because soy farming depends heavily on agricultural inputs and machinery, it is almost solely the domain of wealthy agribusinessmen, and soy farming has been associated with extreme income concentration wherever it has spread in Latin America [38]. As the soy industry is now a major source of foreign currency for Brazil, the needs of soy farmers have been used to justify many of the controversial transport infrastructure projects that are currently underway in Amazonia [24]. These are discussed further in Section 5.

Currently about one-third of the Legal Amazon is classified as protected areas or indigenous lands [29,67]. Indigenous reserves represent 76% of this area and encompass 22.5% of the Amazonian biome. Totally protected areas that do not overlap with indigenous areas account for only 4.9% of the Amazonian biome, and sustainable use areas (most of which are national forests and are subject to industrial logging) represent 9.0% [29,67]. Studies have shown that although status as indigenous land or protected area does provide protection against outright deforestation, these areas are the centre of much of the legal and illegal logging activity that is currently taking place in Amazonia [30]. As they are increasingly surrounded by roads and deforestation, indigenous lands and protected areas are also vulnerable to poaching and to degradation by runaway fires [55,57].

4. Empirical measures of deforestation in the Brazilian Amazon

4.1. Background

The Brazilian National Institute for Space Research (INPE) has produced annual, satellite-based estimates of deforestation since 1989, with the exception of 1993. Types of clearings that contribute to deforestation estimates include pasture, agricultural plots, areas of gold and other mining activity, areas flooded as hydroelectric reservoirs, roads and urban areas. Activities such as selective logging and surface fires that may significantly thin the forest canopy but which do not destroy it entirely are not included in INPE estimates of deforestation [36].

Two trends can be observed in the chart of annual rates of deforestation of 1990–2003 (Fig. 1). The first is that the annual variation in deforestation is large, and the second is that the annual rate of deforestation is accelerating ($r_s = 0.66$; $p = 0.014$). The first trend probably reflects the year-to-year variation in factors that affect the ability of land-users to clear forest, such as disposable income (which in turn might reflect factors such as the state of the national economy and inflation rates) and the length of the dry season (e.g. the long dry seasons of El Niño years facilitate extensive land-clearing with fire) [42,13,15,54,6]. For example, the dramatic jump in deforestation in 1995 has been attributed to the increase in available investment funds following the federal economic reforms in July 1994 that stabilized the Brazilian currency [22]. The sensitivity of the Amazon-wide deforestation rate to annual variation in factors such as export prices will further depend on which economic activities are dominant in the region. For instance, whereas subsistence households are generally not very sensitive to market fluctuations [3], cattle farmers' disposable income (and therefore, ability to clear land) is dependent on local beef markets. However, beef markets in Brazil are relatively stable in comparison to global commodity markets such as the soybean market on which a growing number of Amazonian landowners depend [24]. The forces that drive annual variation are not discussed further in this paper; however, the dramatic jumps in deforestation in 1995, 2002 and 2003 reflect their importance.

The second trend, the acceleration of annual rates of deforestation from 1990 to 2003, is driven by factors at local, national and international levels. The drivers are in some cases difficult to isolate as single, quantifiable variables. Often, however, the factors driving deforestation are measured by government censuses, independent field studies, or satellite-based remote sensing projects. When data for these factors are available, their relationships to deforestation can be assessed empirically.

A number of methods have been used to study the relative contribution of different factors to deforestation; Angelsen and Kaimowitz [3] provide a thorough review of deforestation studies and methodologies. Traditionally, empirical studies have used deforestation estimates based on agricultural census data or on reports of land use by different government institutions (e.g. [2,14,59]). The advent of remote sensing and Geographic Information Systems (GIS) has allowed researchers to link census-based data on demographics and socio-economics to satellite-based data on land-use change (e.g. [49,51,58,69]). Factors that are often included in such analyses include density of or proximity to paved roads, unpaved roads, and rivers; proximity to markets or major population centers; presence of protected areas; climate; and edaphic characteristics. In the following section, we present the results of a spatially explicit analysis of the relationships of deforestation to several of its most-commonly cited driver variables. This study closely follows a study by Laurance and colleagues [49] that examined these relationships for a random sample of 120 sites in the Legal Amazon. However, in the following section, we tackle two methodological issues that were not taken into account in the original study. First, we stratify our sampling not only on deforestation intensity, as was done in the original study, but also on each explanatory variable in turn. This allows us to determine whether the relationship of deforestation to each driver variable changes when sampling is stratified to include a full range of values for the driver variable. Second, for each stratified variable, we draw and analyse ten random samples of 120 sites. This allows us to assess the degree to which our results are influenced by the random selection of sites. Our approach allows us to draw strong conclusions regarding the relative importance of different driver variables to deforestation.

4.2. Methodology

The data analysed in this study were developed by Laurance and colleagues [49]. GIS software (ArcView GIS 3.2) was used to develop compatible spatial coverages for the distributions of deforestation, population density, roads, rivers, soils, annual rainfall and dry-season length for the entire Legal Amazon region (Table 2). A sampling grid of 50 by 50 km grid cells was overlaid on each distribution, and data on deforestation and all predictor variables were extracted for each of the 1867 grid cells. Data sources and methods are consistent with those described in [49], with two exceptions. First, although our soil data are drawn from the same map of the Brazilian Agricultural Research System (EMBRAPA), we reclassified soil units to place much more weight on physical

Table 2
Variables used in analyses

Variable	Units
Deforestation	Percent grid cell deforested
Paved road	Mean distance (km) to unpaved roads for all 1 km^2 pixels in the grid cell
Unpaved roads	Mean distance (km) to paved roads for all 1 km^2 pixels in the grid cell
Urban population size	Total size of urban populations in grid cell; populations were assigned to the grid cell in which the city center fell
Rural population density	Mean rural population density (persons/km^2) for all 1 km^2 pixels in the grid cell
Annual rainfall	Mean annual rainfall (mm) for all 1 km^2 pixels in grid cell
Dry season length	Mean dry season length (days) for all 1 km^2 pixels in grid cell
Soil fertility	Mean soil fertility value for all 1 km^2 pixels in grid cell
Soil waterlogging	Mean soil waterlogging value for all 1 km^2 pixels in grid cell

The sources and steps taken in the development of the GIS coverages for each variable can be found in Ref. [49] and Appendix A of this paper.

restrictions to soil use, as chemical restrictions are more easily corrected through the use of chemical fertilizers; the soil classification scheme is summarized in Appendix A. Second, we withdrew proximity to navigable rivers as a predictor variable from this study, as the original study revealed that the grain of the analysis was too coarse to detect clearing along rivers, and the correlation analyses were, therefore, unable to capture the relationship of deforestation to river access.

In order to minimize the effects of spatial autocorrelation among response and explanatory variables, the original study examined relationships among deforestation and predictor variables for a random sample of less than 10% of the total 1867 grid cells. Sampling was stratified on deforestation intensity, such that an equal number of the 120 sampled grid cells were 0–33.3%, 33.3–66.7%, and $>66.7\%$ deforested. In this study, we replicate this methodology but use two alternative sampling regimes to thoroughly examine the relationship of each predictor variable to deforestation. In the first case, we stratify sampling on deforestation intensity as was done in the original study. In the second case, we stratify sampling on each predictor variable in turn, such that the full range of values of each predictor is present in the samples of 120 cells that are analysed to determine the relationship of the particular predictor to deforestation. Stratifying the data ensures that relationships that might not be detected if only part of a variable's range was included in the analysis can be detected. For example, in the case of the deforestation data, a random sample of the un-stratified data would select almost purely forested cells because most of the Amazon basin is still forested. In this case, statistical determination of relationships of the few deforested cells to the predictor variables would be almost impossible. The original study examined only one deforestation-stratified sample of 120 grid cells. In contrast, for each stratification method, we drew and analysed 10 random samples of 120 grid cells. For each sample, a plot of deforestation versus the values for the predictor variable was examined to ensure regression-model assumptions were met. We performed regression analyses for each random sample, with the percent deforestation arcsine-square root transformed and certain independent variables (distance to paved and unpaved roads and density of rural and urban populations) log transformed to meet regression-model assumptions. This allowed us to assess the sampling error, to ensure that any correlation we detected was not spurious, and to calculate a mean coefficient of determination (r^2) for each predictor. The coefficient of determination describes the percentage of variation in the response variable that is explained by each predictor. We did not perform multiple regression analysis because of the strong co-linearity between some independent variables. The coefficient of determination reported thus represents the total potential variation explained, without accounting for other variables.

4.3. Results

The correlations of all predictors to deforestation were significant at the $\alpha = 0.05$ level for every sample drawn and for every predictor variable, with the exception of the soil variables (Fig. 3). Soil fertility was significantly correlated to deforestation in just 1/10 and 0/10 of the deforestation-stratified and predictor-stratified samples, respectively, and the soil-waterlogging variable in only 2/10 and 3/10 samples, respectively.

When sampling was stratified on deforestation intensity, paved roads were the best predictor of deforestation, with sites closer to paved roads more likely to be deforested. Paved roads explained 38% more variation in deforestation intensity than did unpaved roads. Rural and urban population densities were also strongly correlated with deforestation, with more deforestation in more densely populated areas. Annual rainfall

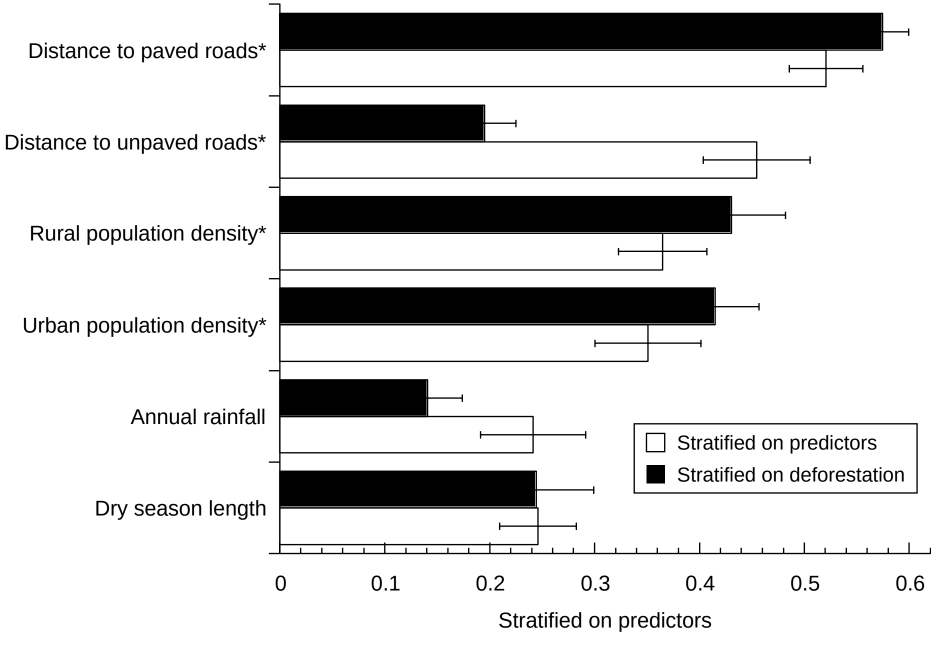

Fig. 3. Mean variation (and 95% confidence intervals) in deforestation explained by each predictor variable when sampling is stratified on deforestation intensity (black bars) and when sampling is stratified on each predictor variable in turn (white bars). Predictors with a '*' were log transformed to meet assumptions of regression analysis.

and dry season length were less important as predictors than paved roads or population density; however, sites with less annual rainfall and longer dry seasons were consistently more likely to be deforested than those with more annual rainfall and shorter dry seasons.

When sampling was stratified on predictor variables, paved roads again explained more variation in deforestation than did any other predictor variable, with the mean coefficient of determination (r^2) within 5% of that for deforestation-stratified samples (Fig. 3). In contrast, the relationship of unpaved roads to deforestation changed dramatically, with roads explaining over 25% more variation in deforestation when sampling was stratified to include a full range of road values. The strength of the correlation of urban and rural population densities was reduced when sampling was stratified to include a full range of population values (by 6.5 and 10% for rural and urban population densities, respectively). Annual rainfall explained 10% more variation in deforestation intensity when sampling was stratified on annual rainfall, however the correlation of dry season length to deforestation changed very little.

All of the drivers examined, therefore, appear to be significant predictors of deforestation at the scale of our study, with the exception of the soil variables. The relationships of the explanatory variables to deforestation under the two stratification methods were relatively consistent, except in the case of unpaved roads, suggesting that this factor in particular merits further investigation.

4.4. Discussion

We found that areas that are accessible by paved or unpaved road, have high population densities, and have relatively low annual rainfall and long dry seasons are more likely to be deforested than are areas with opposite features. Our findings are consistent with those of previous empirical studies that have examined the predictors of deforestation on an Amazon-wide scale [14,49,58,59] (Table 2).

The presence of roads is a strong predictor of deforestation. Previous studies that have focused in particular on the relationship of deforestation to roads have shown that two-thirds of all forest clearing in Amazonia is within 50 km of a major road [56,1]. When sampling was stratified on deforestation intensity we found that paved roads explained more of the variation in deforestation than did unpaved roads. This agrees with the findings of a study by Laurance and colleagues [46] that showed that paved roads have had much farther-reaching effects on the landscapes they traverse than have unpaved roads. This is probably because many of the roads that are currently paved in Amazonia were major government projects that opened access to previously remote areas ('bringing men without land to land without men' [33]). Principal roads also, generally, spawn secondary road networks, with settlement and deforestation gradually spreading outward from the initial cuts through the landscape [51]. These principal roads which connect the many smaller networks are probably the most likely to be paved over the long term.

To date, only one empirical study has suggested that paving roads may in fact slow deforestation. The study incorporated over 50 potential predictor variables into a model and examined the relationships of the predictor variables to deforestation [2]. The study found a negative relationship between paved secondary roads and deforestation, which the authors interpret as evidence that paving roads can stimulate agricultural intensification.

This interpretation has been used to support the many highway-paving projects that are currently underway in the Amazon [32] (see Section 5 for a discussion of current development policy in Amazonia). However, we believe their study suffers from a fundamental weakness: their analyses were based on comparisons of deforestation and other variables at the município (county) level, and because most municípios are located in areas with high population densities and deforestation, their results are unlikely to apply to sparsely populated frontier areas, which are most likely to be impacted by major new highways. Moreover, as interpreted by the authors, the results are, generally, inconsistent with nearly all other empirical studies of deforestation (Table 3).

Overall our study highlights roads as the key component of the deforestation process. Perhaps the most striking finding of our study was the change in the strength of the relationship of deforestation to unpaved roads when sampling was stratified to include a full range of road values. When areas with no unpaved roads and, therefore, no access are explicitly included in the samples of sites analysed, it becomes clear that without road access, there is virtually no colonization and deforestation.

Urban and rural population densities are strongly related to deforestation. Both variables were log transformed, which means that the change in deforestation caused by the first 10 people is equivalent to that caused by the 11th to 100th persons, and to the change caused by the 101st to 1000th persons and so on. Our results, therefore, support the findings of previous studies that the first settlers in a region have a greater effect on the growth of deforested areas than settlers that arrive later on [58]. Again, they highlight the importance of roads to deforestation—the first settlers are unlikely to arrive to a region if it is not accessible by road.

Similarly, there was little additional effect of large-sized cities over small-sized cities on the deforestation of surrounding areas. The highest rates of urbanization in contemporary Amazonia are found in inland settlement frontiers where mining, timber extraction, and other resource sectors are the dominant economic activities [8]. The process of farm establishment is ongoing in these areas, and in support of our results Browder and Godfrey [8] have shown that the process of urbanization is associated with higher, not lower, rates of deforestation. Farms owned by urban residents (‘absentee owners’) are, generally, more deforested than those owned by rural residents. For example, in a 1990 sample of farms, urban-resident farms were 24% more deforested than rural-resident farms. This is because urban-resident landholders generally employ extensive land uses in order to maintain cleared forest, securing their tenure [8]. By the time cities can be considered ‘large’ population centres (i.e. more than 100,000 residents), it is likely that most of the immediate surrounding areas have long been farmed, so additional immigrants to large cities would not translate into the same increases in deforestation as would new immigrants to small cities.

We also found that drier, more seasonal forests were more likely to be deforested. Support for a relationship between dry-season length and deforestation does not appear to merely reflect the concentration of drier forests along the arc of deforestation. For example, Roraima state, which contains extensive seasonal forests, has experienced high rates of deforestation despite its location in northern Amazonia far from major population centres [49]. Our finding of a more significant relationship between deforestation and annual rainfall when sampling was stratified on rainfall suggests that this sampling regime

Table 3
Results of five Amazon-wide studies of the predictors of deforestation

Study	Reis and Margulis 1991 [59]	Pfaff 1999 [58]	Chomitz and Thomas 2001 [14]	Laurance et al. 2002 [49]	This study
Response variable	Extent of deforestation (census/agency reports)	Cleared land density (satellite)	Proportion of area under agriculture (census)	Deforestation (satellite)	Deforestation (satellite)
Extent of study	Legal Amazon	Legal Amazon	Legal Amazon	Legal Amazon	Legal Amazon
Unit of analysis	Municipality	Municipality	Census tract	50 by 50 km cell	50 by 50 km cell
Year of response variable data	1983–1987 depending on state	1988	1996	1999	1999
Proximity to or density of roads	+	+	+	+	+
Density or extent of previously cleared land[a]	+	+	+	Not tested	Not tested
Proximity to or density of rivers[b]	Not tested	−	−	−	Not tested
Population density	+	+	+	+	+
Annual rainfall	Not tested	Not tested	−	−	−
Aptitude of soil for agriculture	Not tested	+	+	0	0
Density of protected areas	Not tested	−	Not tested	Not tested	Not tested

[a] Reis and Margulis [59] use area of municipality in farms.
[b] All studies discount negative results as statistical artefacts.

was better able to capture the significant drop in agricultural land uses in zones with over 2000 mm of rainfall per year [14]. Sombroek [64] hypothesized that high rainfall and short dry seasons may limit agriculture in some regions of the basin because the increased wetness generally means that there is more disease, forest burning is less complete, grains and other crops such as soybeans are more susceptible to rotting, mechanization is more difficult, and rural access roads are difficult to build and maintain.

In contrast to our study, other studies we reviewed that included soil quality as a predictor variable found soil fertility to be positively related to deforestation. There is little detailed information on the distribution of soils in Amazonia, and our lack of a result, therefore, probably reflects both the coarse scale of our soil data and the large size of our units of analysis (50 by 50 km grid cells). Soils vary at much finer scales than these, and landholders similarly make decisions to deforest at a scale of a few hectares, and not of a few hundred hectares.

A recent study that used 30 by 30 m ‘pixels’ of landscape as its unit of analysis appeared to be much better suited to examining relationships between local biophysical conditions and deforestation [51]. The study used relief as a proxy for soil quality, and found that the presence of relief was a significant deterrent to deforestation. However, the relationship weakened over time, and the authors suggest that as land in their study region became scarce, new colonists were willing to settle in areas with less desirable soils. The change in the strength of the relationship over time is a particularly important finding because it suggests that biophysical variables that may initially discourage deforestation may not deter deforestation as land becomes less available. Other studies have shown that previous clearing is one of the strongest predictors of new deforestation, and that deforestation appears to spread inertially from initially cleared sites [1,58,14]. This further suggests that, at a local scale, the influence of biophysical variables on deforestation may weaken over time. The improvement of market, transport, and social infrastructure around initial settlements may counteract any negative biophysical aspects of surrounding areas.

In conclusion, at an Amazon-wide scale, we show that proximity to roads is the best predictor of deforestation. Sites that are densely populated, have severe dry seasons, and receive less annual rainfall are also more likely to be deforested. Although these relationships were reported by Laurance and colleagues [49], our sensitivity analysis confirms them. Our results are also supported by previous studies. These studies show that when time is taken into account, roads again emerge as the key component of the deforestation process. Population and secondary roads follow in importance [51]. Biophysical variables such as rainfall and soil fertility appear to mediate the extent of deforestation in an area given the presence of these other factors; however, the effect of biophysical factors on deforestation may weaken over time as demand for forested land in an area increases.

5. Future of forests in the Brazilian Amazon

Although a goal of Brazilian development policy throughout the last four decades has been to integrate the Amazon into the national economy, the scale of the plans for Amazonian development that were unveiled in the country’s 2000–2003 federal development plan was unprecedented. ‘Avança Brasil’ (Forward Brazil) included over

US$40 billion in planned infrastructure and energy projects for the Legal Amazon region alone [26]. All of the proposed projects either focussed on road improvements or would require road access, with the majority of investment directed to export-oriented activities including projects that would link the soybean producers of north-central Brazil to Amazon River ports, develop new sources of hydroelectric energy for aluminium processing, and exploit gas reserves in the remote western part of the basin.

Early criticism of Avança Brasil for its environmental short-sightedness and apparent "disconnect[ion] from social and rural development policies that could improve the population's quality of life" triggered a storm of controversy in Brazil [12,46]. Some of the planned projects were stalled in order for environmental impact assessments to be carried out, while others have yet to be funded. However, many have gone ahead or are inprogress [56]. The development of these projects will take place in the context of already-accelerating rates of deforestation in Amazonia (Fig. 1). This acceleration can be expected to continue even in the absence of new development projects given the high rate of migration to Amazonia driven by the tremendous number of landless poor throughout Brazil, the still substantial (albeit declining) intrinsic growth rate of the Amazonian rural population, and the growing dominance of large-scale agricultural activities in old frontiers [10,43,47].

Several studies have attempted to model the effects of the planned projects on the future of Amazonian forests. One spatially explicit modelling effort predicted that Avança Brasil, in addition to other federal development projects planned for the Amazon region in 2001, would drive an increase in the annual deforestation rate of 14.3–26.8%, leaving 28–42% of the basin deforested or heavily degraded 20 years from now [46]. A second modelling study, which focussed specifically on the potential effects of the road projects proposed under Avança Brasil, predicted a net increase in deforestation and forest impoverishment through logging and fire of 120,000–270,000 km^2 [56]. Overall, these studies suggest that the 7284 km of roads initially listed to be paved under Avança Brazil would almost double the area of forest land that is currently accessible by paved roads, and would come within 50 km of 22 conservation areas and 89 indigenous lands [12,46]. Furthermore, the roads would result in large-scale fragmentation of pristine areas of the basin [12,46,56]. Forest fragments are more vulnerable to logging, hunting, and fire, and are also more accessible to settlers and land speculators [15,50,55,57].

Government ministries promoting the large-scale infrastructure projects have argued that recent changes in enforcement capabilities, laws, and public attitudes will prevent the patterns of deforestation around new roads and highways that occurred in the past from arising again [48,63]. However, two recent trends suggest that institutional mechanisms are not yet strong enough to counteract the drivers of deforestation. The first is the dramatic jump in deforestation in 2002 and 2003; in both years, the weak Brazilian Real meant that export earnings—and, therefore, disposable income—among soy and cattle farmers were high, and 2002 was also an unusually dry year, facilitating the clearing of land with fire [27,39]. The second is the rush of immigration and deforestation that is already taking place in areas where large projects were planned under Avança Brasil but where they have not yet been initiated (or in some cases even secured funding) [9]. The first migrants to these areas are generally loggers and small farmers drawn by the prospect of future work.

Proponents of Avança Brasil have also argued that the location of some paved roads in wetter areas of the basin will discourage deforestation near those roads [4]. Although we found that areas with longer dry-seasons are more likely to be deforested, recent research at local scales shows that biophysical deterrents to deforestation may weaken as land becomes scarce [51]. Given the growing demand for land in Brazil, including the demands arising from over 25 million landless farmers in 2003, we do not believe that the location of some new paved roads in wetter areas of the basin will deter settlement and deforestation in these areas [43].

Critics of Avança Brasil had hoped that the presidency of centre-left candidate Luiz Inácio Lula da Silva that began in January 2003 would mean a new approach to Amazonian development [61]. In appreciation of the development-conservation dilemma faced by the government, some groups proposed 'sensitive development' policies that would bring maximum benefits to local populations while causing minimal extra deforestation. For example, instead of paving federal roads through currently difficult-to-access regions such as the area traversed by the Cuiabá-Santarém road, road improvements could instead be targeted at secondary roads that connect disjoint rural communities in Amazonia. Carvalho and colleagues [11] argue that this would provide the communities with improved access to markets and social services while causing little superfluous deforestation.

However, the draft of the 2004–2007 plan reveals the decision of the Lula government to rely on development projects that aim to increase agricultural production and swell exports [17]. The new plan includes most of the projects initially proposed under Avança Brasil, as well as some ambitious new projects, such as a road that will connect Roraima state to Georgetown, Guyana [5]. Why does federal-level planning for the Amazon region continue to focus on this type of development? Certainly, the government is under significant political pressure to fulfil campaign promises to create jobs, feed the urban poor, and boost the national economy before the end of its 4-year term. Projects that will generate foreign earnings are particularly attractive as the government must also manage debt-service payments, which in 2002 were equivalent to 69% of the country's export earnings [16]. A further attraction of the proposed projects is that many are to be funded by international partners, and will, therefore, require minimal investments on the part of the Lula government.

In a search for alternative development pathways, some research groups have examined the opportunity costs of proceeding with proposed development projects in terms of payments for environmental services. Initial estimates of the economic value of the carbon stocks and biodiversity of the Amazon suggest that investing in their protection might be highly profitable for Brazil over the long-term [16,23]. Other work has focussed on working at the level of the 'agents' of deforestation under the argument that it is individual soy farmers, cattle ranchers, or small-scale farmers who ultimately make decisions to clear forest. According to this view, if these individuals do not perceive the value of forested land as being greater than the value of deforested land, they will have little incentive to leave the forest standing [65]. Section 3 of this paper discusses some of the credit and financial incentives that historically have driven Amazonian landholders to deforest their land, and also suggests that factors related to land tenure, the cost of chemical fertilizers, and strong export markets for soybeans and cattle may continue to provide strong incentives to deforest in the future.

Currently, experiments are underway in many parts of the Amazon with a view to developing forest-dependent land uses that provide livelihood benefits to local inhabitants, and thus incentives to maintain forests. Examples of such land uses include the sustainable management of forests for timber and non-timber products, ecotourism, and the establishment of landowner-level payments for biodiversity conservation and carbon storage [7,62]. One of the most ambitious examples of this type of approach comes from the state of Acre in the southwestern Amazon, where the recently re-elected state government has developed innovative forest policies that emphasize 'neoextractivism' of forest goods and services. The state is actively working to facilitate production, value-added processing, and marketing of forest products, while ensuring that extraction methods are sustainable over the long-term [40]. Between 1999, when the government's new rubber policy was implemented, and 2002, natural rubber production in the state tripled, and the number of families supported by rubber production increased from 1480 to 6154 [40].The success of Acre's conservation-oriented approach to development has been attributed in part to its long history of commercial extractivism and thus its institutional capacity in this area, as well as to the relatively low pressure on the state's forests until 1992, when the stretch of highway that connects Acre to southern Brazil was paved [40]. We suggest that in parts of the Amazon where institutions are relatively weak, settlement is unorganized, land tenure is illegal, and deforestation is often highest, initiatives focused on the sustainable extraction of forest products or payments for environmental services will be very difficult to implement in the short-term. The 2004–2007 plan for a large-scale expansion of transport infrastructure will greatly expand such 'frontier' areas in the Amazon.

In late 2003, those fighting for a re-evaluation of the projects proposed under the 2004–2007 plan were provided with new hope. In their final report, the 'Interministerial Working Group on Deforestation', formed by presidential decree in July 2003 to scrutinize the Amazonian deforestation issue, called for the re-evaluation of a number of planned infrastructure projects based on the projects' potential to 'open a new front of occupation' and 'reproduce the [destructive] model of development which has predominated in Amazonia over the last 20 years.' [45]. So far, the Lula administration has not opted to cancel or substantially delay any of the planned infrastructure projects, but rather is pushing ahead with the projects as fast as financial restrictions allow and licensing hurdles can, at least nominally, be overcome.

In conclusion, planners and policy makers for the Brazilian Amazon urgently need to consider the potential effects of planned development on Amazonian forests. Based on the evidence from this study, and the compiled evidence from previous studies, we make the following recommendations.

1. The construction and paving of roads and highways in the Amazon region should be curtailed until environmental impact assessments and economic cost-benefit analyses for local communities have been carried out. All empirical evidence reviewed suggests that paved and unpaved roads are the two factors most strongly correlated with deforestation, and benefits of road development projects to Amazonian communities

are far from certain given the focus of current development plans on providing export-oriented industries in Central Brazil with quicker access to Amazon River ports. It is essential that very careful planning be undertaken before the roads or highways are built, as once people have access to forests, a Pandora's Box of new challenges to forest conservation is opened.

2. Efforts by the Brazilian government and external agencies working in conjunction with the government to establish a network of protected areas in the Legal Amazon should focus in particular on forests that experience strong dry seasons. The vulnerability of drier forests to deforestation suggests that deciduous and semi-deciduous forests, woody oligotrophic vegetation (e.g. *campina* and *campinarana*), and ecotonal forests of the cerrado-rainforest interface should be given a priority for conservation. These areas are currently poorly represented in the national system of protected areas [29,28]. Empirical evidence suggests that classifying areas as reserves discourages deforestation, though not all forms of degradation, even if there is little enforcement of their boundaries [27,29,51].
3. Capacity building and engagement of local peoples should be a priority of conservation-oriented activities. In particular, indigenous peoples, whose lands cover 22.5% of the Amazonian biome and overlap with over 70% of Amazonian protected areas, will play a critical role in determining the future of Amazonian forests [27,29,67].
4. Further empirical studies are needed to better understand how specific sets of environmental and socio-economic variables combine to determine deforestation at a local scale. However, if minimizing the loss of additional forest areas is indeed to be a federal priority [60], ample evidence is already available to justify a fundamental change to current development programs that emphasise the expansion of transport infrastructure.

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Appendix A

The soil fertility classification was based on the same EMBRAPA map of Amazonian soils as in the original study by Laurance and colleagues [49] for which the biophysical data were compiled. For the present study, soil units were reclassified into five main classes and four intermediate classes. The lowest class (1), comprising 8% of the basin, contained very infertile soils with no agricultural potential, such as quartz sands and podzols. The second class, comprising 13% of the total area, contained mostly distrophic (nutrient-poor) soils with strong physical restrictions, such as shallowness, high content of concretions, waterlogging, or plinthite. The third class, comprising 20% of the basin, contained highly weathered, acidic, distrophic soils with no severe physical restrictions other than light topsoil and clay enrichment with depth (Ultisols). The fourth class, comprising 21% of the area, contained highly weathered, acidic, distrophic soils with generally favourable physical properties (Oxisols). The fifth class, comprising 5.5% of the basin, contained relatively fertile soils that are nutrient-rich, not acidic, and whose main restrictions are seasonal flooding (varzea soils) or waterlogging (Vertisols). This class also contained the Terra Roxa soils that are sought after for cocoa growing, and other eutrophic soils.

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