

Roads and Deforestation in the Brazilian Amazon

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Summary

New analyses based on greatly improved data clearly reject the recent claim that new roads will slow Amazon deforestation.

Abstract

A controversy is currently raging over the impacts on forests in Brazilian Amazonia of a dramatic planned expansion in highways, unpaved roads, and other major infrastructure. A recent, influential study suggests that road expansion in areas of Amazonia that have already experienced significant development can actually reduce deforestation rates, by concentrating local development pressures. Based on more spatially detailed data, however, we find that in the great majority of Amazonia new roads will significantly accelerate deforestation and that the effect is greater in highly cleared areas (50-75% deforestation). Only in severely deforested areas (over 75%) are the impacts of new roads non-significant and they never diminish the rate of forest loss. These findings clearly reject the notion that road expansion will slow Amazonian deforestation.

The pace of land-cover change in the Amazon Basin is of international importance given the region's exceptionally high biodiversity and the key role that its forests play in global carbon and hydrological cycles. In the early 1960s, the Brazilian government began to build roads linking the Amazon to other parts of the country. Since then, over 16% of Brazil's 'original' (pre-Columbian) Amazonian forest has disappeared and the rate of forest loss—currently averaging about 2.4 million ha per year—is accelerating (*I*).

In 2000, a Brazilian-government initiative originally known as ‘Avança Brasil’ (Advance Brazil) called for paving an additional 7500 km of highways in Amazonia for a range of development objectives, including expansion of mechanized soybean agriculture for export (2, 3). Some projects have been widely discussed, such as paving the 900 km BR-163 highway (4), which would facilitate soy exports. Avança Brasil also calls for an investment in unpaved roads, gas and power lines, hydroelectric dams, river channels and railroads. These initiatives raise a crucial policy question, namely, how much forest will be lost as a result of such investments in new infrastructure for regional development?

Laurance et al. 2001 (2) presented scenarios of future forest loss in the Amazon based on assumptions about the impacts of infrastructure on forest cover. Their models suggested that, should all the Avança Brasil projects proceed, 28% of the pre-Columbian forest would be lost by 2020 under an “optimistic” scenario, whereas 42% would be lost under a “non-optimistic” projection. This assessment of the potential impacts of Avança Brasil stimulated considerable debate, which often focused upon the assumptions made concerning the impacts of new roads on forest cover (5-13).

In a subsequent analysis, Andersen et al. 2002 (14) evaluated Brazilian national-census data for Amazonia to address a range of issues, including the economic benefits from forest conversion (15). Concerning the impacts of roads on forest clearing, they arrived at dramatically different conclusions from those of Laurance et al. 2001. They found that the impact of roads depends critically on the level of previous forest clearing and, most dramatically, that in landscapes with substantial prior deforestation new roads actually *reduce* the rate of deforestation. This, they suggest, is because roads in these circumstances focus local development and draw it away from remaining forest tracts.

Given their potentially profound implications for Amazonian forest management and environmental planning, we re-evaluated the Andersen et al. findings with far more precise data. Andersen et al. employed census data for Brazilian counties (municípios) whose boundaries changed markedly during their study interval. To compare the 1970s with the 1990s required substantial aggregation of 1990s counties. This resulted in their sample of 257 county units (quite large on average although varied in size) for the entire Brazilian Amazon. Though the census data they employed are useful for both temporal coverage and socioeconomic content, the sampling units greatly constrained the analysis.

To overcome this constraint, we employed a greatly expanded dataset to assess the impacts of roads upon Amazonian forest cover. Like Andersen et al., we estimated roads' impacts based on careful inference from observations of past deforestation, with statistical controls for other influences on land use. However, we used highly spatially disaggregated data with 26 times as many observations. Our smaller sampling units (700 km² average size in Table 1), termed census tracts, allow more precise quantification of both roads (Fig. 1) and deforestation, provide greater statistical power, and permit a far more direct assessment of how the impact of roads varies with the level of prior clearing.

Our analyses employed over 6700 census-tract observations across space to study the drivers of deforestation for an eleven-year period, from 1976 to 1987 (16), following the first major era of highway expansion. We confined our study to this early interval to allow a direct focus on new paved roads' (Fig. 2) impacts on Amazonian forests. Not only do roads lead to deforestation, but also deforestation and local development cause new roads by providing a political and economic impetus for further road building (17, 18). To help distinguish these two effects and specifically to focus upon roads' impacts,

we chose this time period and as our explanatory variable we used ‘lagged’ new roads, i.e. the roads constructed during 1968-1975, to explain the 1976-1987 deforestation.

Using digital maps of roads and forest cover, we tracked the evolution of roads and forest clearing within each census tract (19). We also integrated maps of ecological conditions (rainfall, soil fertility, slope, previous deforestation) and distances to markets to control for their influences in testing our hypotheses about roads (20). Our statistical approach (21), which applies concepts used in most economic land-use models (10-18), also exploits our numerous sampling units by implementing statistical controls for the influences of unobserved factors that are shared by census tracts within the same county (e.g., soil qualities that are not in our data set and whose values are spatially correlated). This is a critical advance in controlling for many non-road influences on deforestation.

Like previous studies (1, 2, 16, 20), our results (Tables 1 and 2) suggest that higher soil fertility encourages deforestation while increased slope and greater distance to markets discourage it (22,23). Also, independent of roads, deforestation is positively associated with prior deforestation (24). Concerning roads, reducing transport costs via paved highways or unpaved roads clearly increases deforestation on average (Table 1).

However, these are basin-wide average effects. If Anderson et al. are correct, then local road impacts on deforestation should decline with previous deforestation and, when the prior clearing is very high, highway paving should inhibit further clearing. We found that new paved highways increase deforestation within the areas that are uncleared (0% deforested) and somewhat cleared (1-50% deforested, Table 2), results that are consistent with those of Andersen et al. (25). In striking contrast to the Andersen results, however, in heavily cleared (50-75% deforested) areas effects of new paved highways are larger

than in less-cleared areas. Thus, over some range of previous deforestation, a higher level can actually increase the impacts of new roads. This might occur because the capital and labor needed to effect further deforestation are more readily available in heavily cleared areas, which already have more established populations and local economies.

Another key disparity with the findings of Andersen et al. occurs in very heavily cleared lands (>75% deforested). For these areas, the impacts of paved highways remain positive but smaller in magnitude than in areas with little clearing (26) and the result is non-significant statistically (Table 2). Importantly, under no conditions did highways slow deforestation (27).

In summary, we find no support for the claim that highway and road expansion in Amazonia can reduce either basin-wide average or local deforestation rates. All of the significant coefficients for both the paved-highway and the unpaved-road variables are positive (Tables 1 and 2), indicating that new roads investments will invariably increase forest loss. On this basis, we reject the assertion that new roads can reduce deforestation.

In addition to greater statistical power, our analysis has two major advantages over previous studies. First, the large number of census tracts allowed us to control statistically for the influences of heterogeneity among counties in unobserved factors, such as soil qualities or river access that are not well measured. This is a far finer-scale statistical control than has been used previously; by removing much unobserved variation it greatly improved our ability to identify the true effects of roads on deforestation rates. Second, because of our large data set we could run separate analyses for four different categories of prior forest loss (0%, 1-50%, 50-75%, >75%). With hundreds to thousands

of observations in each category, we greatly refined such estimation of roads' effects on forest (Tables 1 and 2).

The Brazilian government faces enormous pressures to expand the transportation infrastructure in Amazonia, both to satisfy local interest in economic development and to promote export commodities such as beef, soy and timber. On an almost daily basis, difficult decisions are made that involve tradeoffs between economic development and environmental conservation. Our results suggest that new road investments in Amazonia will not yield a “win-win” outcome whereby new infrastructure promotes increased economic growth while simultaneously slowing deforestation. Further, by confirming that road impacts are strongly influenced by prior deforestation, our results show that strategic planning of new roads and highways is critical. When the road investments are concentrated in very highly developed areas, their environmental impacts will usually be far smaller than when they penetrate remote frontiers and intact forests.

References and Notes

1. W. F. Laurance *et al.*, *Science* **304**, 1109 (2004).
2. W. F. Laurance *et al.*, *Science* **291**, 438 (2001).
3. P. M. Fearnside, *Environ. Conserv.* **28**, 23 (2001).
4. D. C. Nepstad *et al.*, *Science* **295**, 629 (2002).
5. S. S. do Amaral, Threat to the Amazon. *The Independent*, London, 26 January (2001).
6. R. Goidanich, *Science dEbate*s, 26 January (2001) (www.sciencemag.org/cgi/eletters/291/5503/438).
7. J. P. Silveira, *Science* **292**, 1651 (2001).
8. D. Weber, Ministério contesta estudo sobre devastação. *O Estado de S. Paulo*, São Paulo, Brazil, 21 January (2001).
9. See alternative derivations of parameters from observed deforestation in refs. 10-13.
10. R.N. Stavins, A. Jaffe, *Am. Econ. Rev.* **80**, 337 (1990).
11. E.J. Reis, R. Guzman, *An Econometric Model of Amazon Deforestation*, IPEA, Rio de Janeiro, Brazil (1992).
12. G.C. Nelson, D. Hellerstein, *Am. J. Agric. Econ.* **79**, 80 (1995).
13. A. Pfaff, *J. Environ. Econ. Manage.* **37**, 26 (1999).
14. L.E. Andersen *et al.*, *The Dynamics of Deforestation and Economic Growth in the Brazilian Amazon*, Cambridge Univ. Press (2002).
15. Their work (ref.14) advanced methodologically the study of Amazon deforestation. Their use of lagged road changes to explain deforestation is applied here too. They also put significant effort into an objective method for choosing among regressions.

16. K.M. Chomitz, T.S. Thomas, *Am. J. Agric. Econ.* **85**, 1016 (2003) used census-track data, emphasizing the importance of ecological constraints, but lacked the data over time for the type of test of roads' impacts on forests implemented here or in ref. 14.
17. K.M. Chomitz, D. Gray, *World Bank Econ. Rev.* **10**, 487 (1996).
18. M. Cropper *et al.*, *Land Econ.* **75**, 58 (1999).
19. The deforestation maps were produced in 1997 by IBGE (Instituto Brasileiro de Geografia e Estatística) for the "Diagnostico Ambiental da Amazonia Legal". Pre-1976 clearing is from the RADAM Project vegetation maps with classes of land cover. Clearing in 1987 is from IBAMA/INPE maps based upon Landsat imagery. The digital road maps were developed in the Department of Geography at Michigan State University from paper maps produced by DNER (Departamento Nacional de Estradas de Rodagem) within the Ministry of Transport in Brazil. The digital maps we used show the distribution of paved and unpaved roads for 1968 and 1975. For both years, we measured the length of paved and unpaved roads for each of the 1996 Legal Amazon census-tract polygons and then calculated the changes in paved and unpaved road density for 1968-1975.
20. W.F. Laurance *et al.*, *J. Biogeography* **29**, 737 (2002).
21. The dependent variable is the fraction of 1976 forest that was cleared by 1987. This aggregates many binary decisions about whether to clear forest, so a Grouped Logit specification is appropriate (W.H. Green, *Econometric Analysis*, Macmillan 1990). Grouped Probit models yield very similar results. Independent road variables include the changes in census-track density during 1968 to 1975 (i.e., change in length of roads of either type divided by area of the census tract). They also include

an index of soil quality, binary variables indicating slope categories, and continuous rainfall data (20). Distance to the nearest city is computed using both a small set and a much larger set of cities (see ref. 29). These city distances are used simultaneously to represent transport costs, indicate proximity to a very large city, and eliminate census tracts close to cities from the analysis. Note that a robustness check in which no tracts are dropped for being near to cities finds the same results.

22. When we reduce our spatial controls to the state level, rainfall and distance to the nearest river become significant.
23. T.K. Rudel, B. Horowitz, *Tropical Deforestation*. Columbia Univ. Press (1993).
24. This is consistent with previous work in S. Kerr, A. Pfaff, A. Sanchez, *Development and Deforestation* (2003), Unpubl. Tech. report [www.columbia.edu/~ap196].
25. Unpaved roads also increase deforestation rates in uncleared and somewhat-cleared areas but their effects are non-significant in the highly and extremely cleared areas.
26. For relevant theory see D.W. Jones, R.V. O'Neil, *Ecol. Econ.* **6**, 79 (1992).
27. If anything, we are being conservative by commenting on the average effects from all paved road investments in this period. The Amazonas segment (Fig.2), known to have generated relatively little development, had little effect on clearing while the Belem-Brasilia segment that stimulated more development had large positive effects on clearing. Our average effect blends the effects of all of these paving investments. If all future road investments will stimulate development then our estimates are low.
28. The dependent variable is the fraction of the 1976 forest area deforested by 1987. For this aggregation of individual clearing choices, a Grouped Logit specification addresses the heteroskedasticity due to the variation in size across the census tracts.

29. Basic Regression drops about 100 census tracts near 19 large cities (within 20km of a city with population density over 100 people/km²). As a robustness check, Using More Cities drops about 1000 tracts near 270 medium and large cities (within 20km of a city with population density over 11 people/km²) and dropping no tracts yields very similar results. 'Distance To City' is measured using the 19 large cities for the Basic Regression but using the 270 medium and large cities for Using More Cities. In each regression, 'Next To Big City' equals 1 if a census tract is within 50km of a city with population density over 500 people/km² (there are five); else, it equals 0.
30. When county-level fixed effects are not included, the 'Distance To River' variable is significantly negative and the rain and slope coefficients are more significant. When rainfall is significant the linear effect is positive, quadratic is negative etc., and it is important to understand that this impact is greatly absorbed by the fixed effects. For our purposes that is not a problem, as we are only controlling for rain.

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Tab. 1. Regressions that control for impacts of various non-road factors on Amazonian deforestation in testing for the impacts of roads investments (28). These regressions use all census-track observations (29) without regard to previous clearing (unlike in Table 2). Regression coefficients are shown with *t*-statistics in the parentheses (30).

<u>Explanatory Variables</u>	<u>Basic Regression</u>	<u>Using More Cities</u>
Paved Highways	10 (6.6)	13 (7.1)
Unpaved Roads	63 (9.2)	74 (10)
Cleared % in 1976	3.1 (18)	2.7 (14)
Distance to City	-0.001 (3.9)	-0.004 (15)
Next To Big City	1.2 (2.6)	1.6 (3.1)
Distance to River	0.001 (5.2)	0.001 (2.0)
Rain Linear	-0.003 (0.4)	0.03 (3.6)
Rain Quadratic	2×10^{-06} (0.3)	-2×10^{-05} (3.8)
Rain Cubic	-5×10^{-10} (0.3)	6×10^{-09} (3.6)
Rain Quartic	6×10^{-14} (0.4)	-5×10^{-13} (3.4)
Slope – rock outcropping	-4.1 (3.2)	-3.4 (2.6)
Slope – steep	-0.66 (1.1)	-0.84 (1.4)
Slope – mountainous	-0.90 (4.4)	-0.67 (3.2)
Slope – strongly hilly	0.08 (0.5)	-0.002 (0.0)
Slope – hilly	-0.07 (0.7)	0.08 (0.9)
Slope – gently hilly	0.19 (3.3)	0.28 (4.7)
Soil Fertility	0.25 (13)	0.23 (11)
Constant	1.1 (0.3)	-15 (4.3)
County Fixed Effects	significant	significant
<u>Adjusted R²</u>	0.45	0.47
<u># Observations</u>	6747	5859

Tab. 2. Re-analysis of the “Basic Regression” model in Table 1 but using only census tracks with specific levels of prior deforestation (given in the column headings).

Regression coefficients are shown with *t*-statistics in parentheses.

<u>Prior Deforestation:</u>	<u>0 %</u>	<u>1-50 %</u>	<u>50-75 %</u>	<u>75-100 %</u>
<u>Explanatory Variables</u>				
Paved Highways	11 (5.8)	10 (2.7)	21 (2.6)	3.6 (0.7)
Unpaved Roads	71 (9.1)	53 (2.8)	11 (0.3)	-1.7 (0.1)
Cleared % in 1976	-----	2.8 (6.2)	0.95 (0.5)	2.0 (1.3)
Distance to City	-0.001 (2.9)	0.001 (0.9)	0.004 (1.0)	0.01 (1.8)
Next To Big City	1.1 (0.9)	-0.14 (0.1)	1.9 (2.6)	-0.2 (0.4)
Distance to River	0.001 (3.2)	0.01 (5.2)	0.01 (2.1)	0.01 (2.3)
Rain Linear	0.01 (1.3)	0.11 (1.1)	0.18 (0.5)	0.37 (1.2)
Rain Quadratic	-5×10^{-06} (1.0)	-9×10^{-05} (1.2)	-1×10^{-04} (0.6)	-3×10^{-04} (1.2)
Rain Cubic	8×10^{-10} (0.6)	3×10^{-08} (1.2)	5×10^{-08} (0.6)	9×10^{-08} (1.2)
Rain Quartic	-4×10^{-14} (0.3)	-4×10^{-12} (1.2)	-7×10^{-12} (0.7)	-1×10^{-11} (1.2)
Slope – rock outcropping	-10 (5.5)	0.50 (0.2)	-----	-----
Slope – steep	-2.2 (3.2)	3.1 (2.0)	-12 (1.3)	-----
Slope – mountainous	-1.0 (4.9)	-0.45 (0.7)	-14 (2.0)	-24 (5.5)
Slope – strongly hilly	-0.07 (0.5)	-0.21 (0.5)	-2.7 (1.7)	-0.38 (0.3)
Slope – hilly	-0.08 (0.9)	-0.07 (0.3)	2.1 (2.2)	0.54 (0.7)
Slope – gently hilly	0.07 (1.2)	0.48 (2.6)	-0.54 (1.0)	1.6 (4.1)
Soil Fertility	0.24 (11)	0.32 (5.3)	-0.22 (0.8)	0.35 (2.8)
Constant	-7.7 (1.8)	-50 (1.1)	-93 (0.6)	-184 (1.2)
County Fixed Effects	significant	significant	significant	significant
<u>Adjusted R²</u>	0.45	0.49	0.60	0.73
<u># Observations</u>	5376	933	205	233

FIGURE LEGENDS

Fig. 1. Comparing the more precise unpaved road data for this study's over 6700 census tracts to that for Andersen et al.'s (ref. 14) 257 counties. Red areas are census tracts that in fact had no unpaved roads either in place or being built in 1975 but were indicated as having unpaved roads in the county data.

Fig. 2. Paved highways in Brazilian Amazonia in 1968 (red) and 1975 (red and purple).

Fig. 1

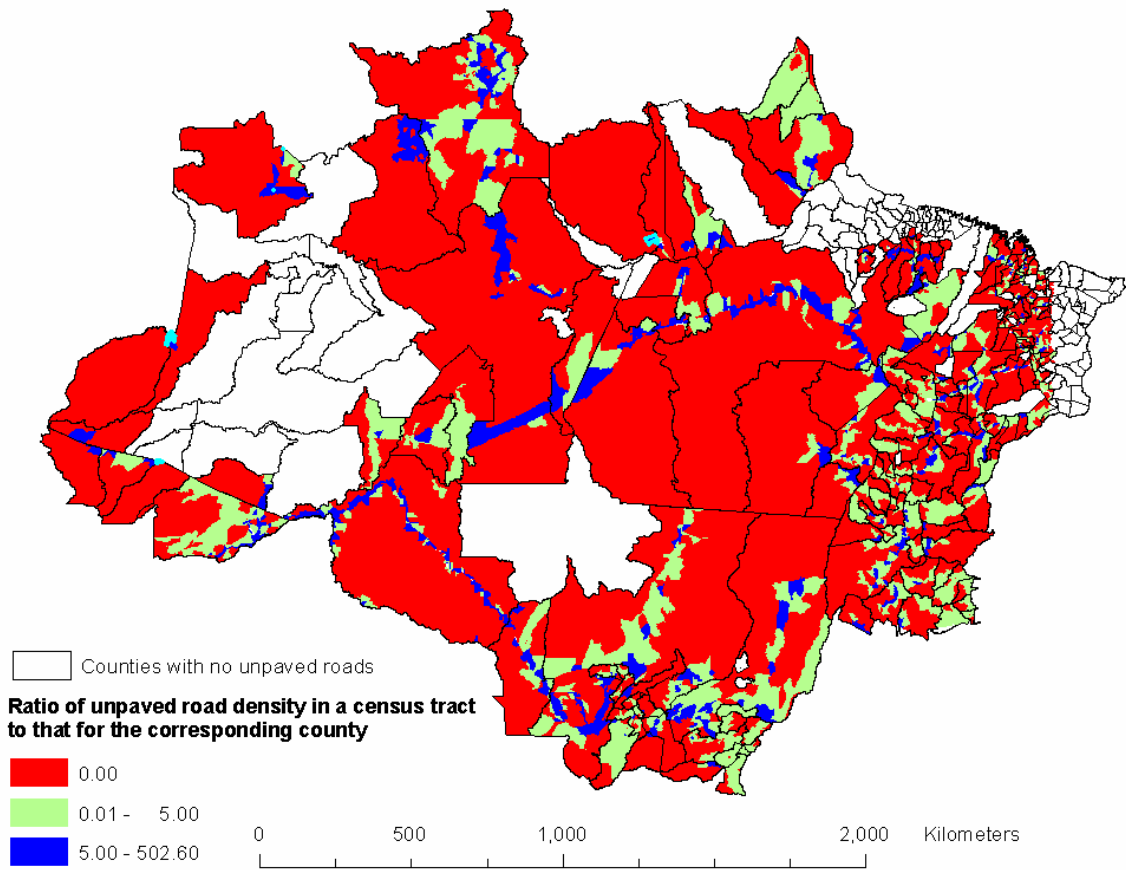


Fig. 2

