Boom-and-Bust Development Patterns Across the Amazon Deforestation Frontier

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The Brazilian Amazon is globally important for biodiversity, climate, and geochemical cycles, but is also among the least developed regions in Brazil. Economic development is often pursued through forest conversion for cattle ranching and agriculture, mediated by logging. However, on the basis of an assessment of 286 municipalities in different stages of deforestation, we found a boom-and-bust pattern in levels of human development across the deforestation frontier. Relative standards of living, literacy, and life expectancy increase as deforestation begins but then decline as the frontier evolves, so that pre- and postfrontier levels of human development are similarly low. New financial incentives and policies are creating opportunities for a more sustained development trajectory that is not based on the depletion of nature and ecosystem services.

The Brazilian Amazon harbors 40% of all remaining tropical rainforest (*1*), playing a vital role in global biodiversity conservation (*2*), climate regulation (*3*), and biogeochemical cycles (*4*). An average of 1.8 million hectares of forest has been lost annually during the 1988–2008 period as agricultural land uses expand (*5*), corresponding to nearly one-third of global tropical deforestation (*6*) and releasing about 250 million tons of carbon (*3*, *7*). Yet this is also one of the least developed regions in Brazil (*8*), and conversion of forest for agriculture and cattle ranching (typically preceded by logging and burning) is often seen as the most practical route to achieving legitimate aspirations to economic development (*9*). Here, we investigated how human development varies across the region's deforestation frontier to determine whether deforestation is associated with a sustained improvement in people's well-being.

The Brazilian Amazon is well suited to exploring trade-offs between development and conservation because habitat conversion is proceeding quickly—compressing into decades a process that took centuries or millennia in many other parts of the world—and because socioeconomic conditions are systematically documented (*8*, *10*). Furthermore, although the Brazilian Amazon is by no means a homogeneous region, it has relatively limited variation in the potentially confounding factors (such as geography, history, and governance) that have been shown to explain variation in wealth at the global scale (*11*).

One measure used to assess levels of development is the human development index (HDI), calculated following a standard procedure developed by the United Nations Development Programme (*12*). The overall HDI is calculated as the mean of three subindices: life expectancy (based on life expectancy at birth), literacy (based on literacy rate and school enrollment), and standard of living (based on per capita income); it thus offers a measure of human development that is more comprehensive than measures based solely on per capita income (*12*). We obtained HDI values from the 2000 Brazilian Atlas of Human Development for 286 municipalities in the Brazilian Amazon (*8*). Municipalities were grouped into seven classes (A to G) describing their position relative to the deforestation frontier in 2000, defined according to both deforestation activity and deforestation extent (*5*) (Fig. 1 and fig. S1). The classes range from prefrontier municipalities, with essentially intact forest cover and virtually no ongoing deforestation (A), through progressively deforested classes, with increasing (B to D) and then declining (D to F) deforestation activity, through to heavily deforested postfrontier municipalities that were again almost inactive in terms of deforestation (G) (Fig. 1). The current wave of deforestation began with government colonization schemes on the eastern and southern borders of the region in the early 1970s, extending westward and along the southern fringes through the 1980s, forming an "arc of deforestation" that is still expanding into the heart of the Amazon (*5*).

When the median HDI of each class is plotted against deforestation extent, a boom-and-bust pattern becomes apparent (*9*, *14*), which suggests that relative development levels increase rapidly in the early stages of deforestation and then decline as the frontier advances (Fig. 2A). Hence, although municipalities with active deforestation had development levels that approached the overall Brazilian median, pre- and postfrontier HDI

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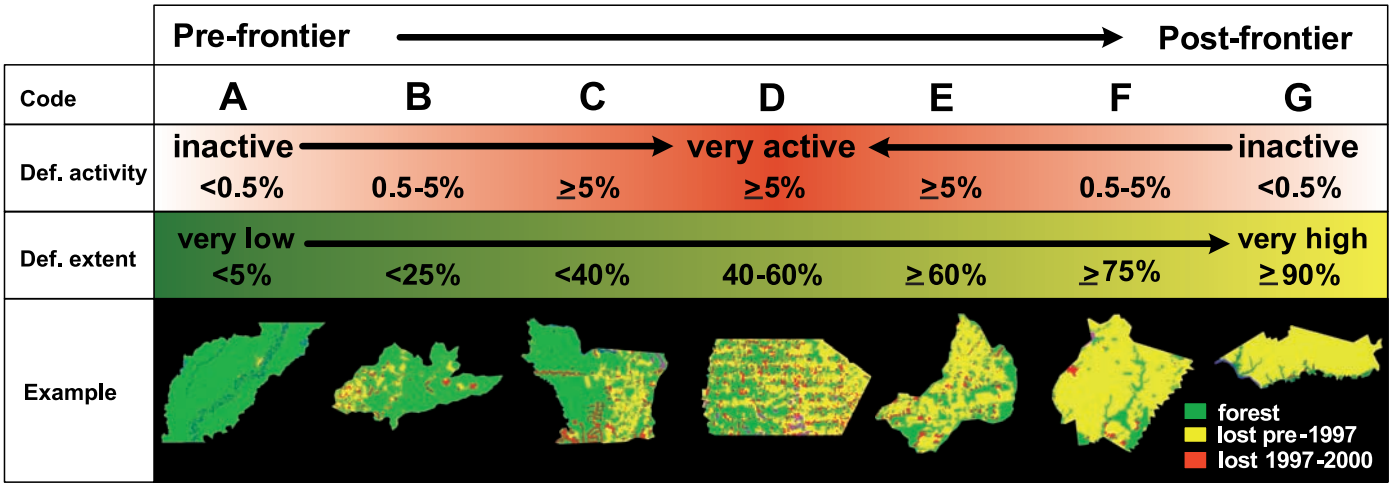

Fig. 1. Definition of frontier classes A to G according to recent deforestation activity (percentage of municipality area deforested between 1997 and 2000) and deforestation extent (percentage of the original forest that had been lost by 2000). A representative municipality is mapped as an example of each class (spatial scale variable) (*5*, *13*).

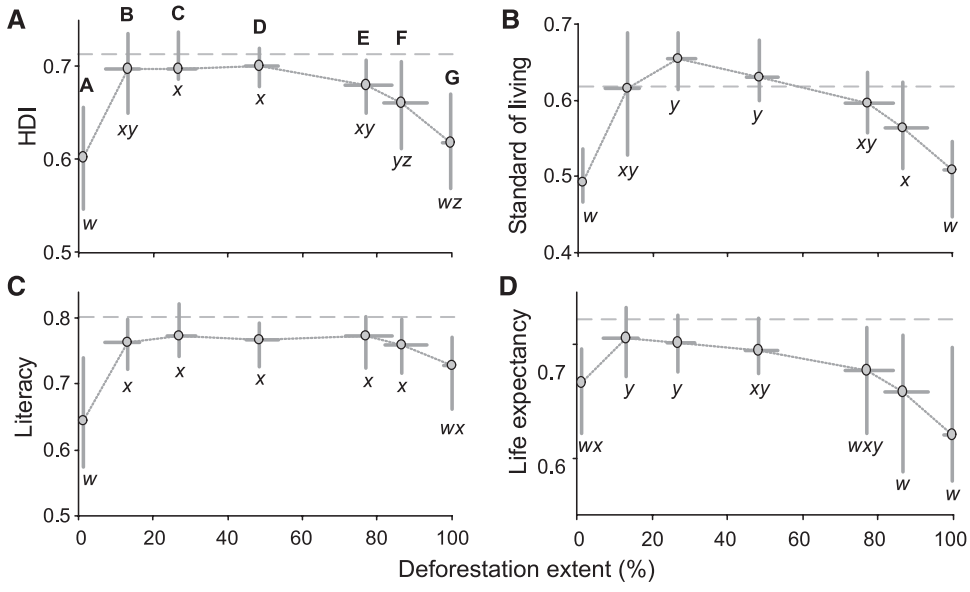

Fig. 2. Variation along a deforestation gradient (*5*) corresponding to frontier classes A to G, as defined in Fig. 1, in (**A**) the human development index (HDI, obtained by averaging the subindices on standard of living, literacy, and life expectancy); (**B**) the standard-of-living subindex (based on per capita income); (**C**) the literacy subindex (based on literacy rate and school enrollment); and (**D**) the life expectancy subindex (based on life expectancy at birth) (*8*). As labeled in (A), circles from left to right correspond to classes A to G in all panels. Circles indicate median values; bars indicate first and third quartiles; horizontal dashed line indicates the median across all Brazilian municipalities. All variables present significant variation across the frontier classes (Kruskal-Wallis: $P < 0.0001$); classes that do not have a letter (*u*, *v*, *w*, *x*, *y*, *z*) in common differ significantly (Tukey's honestly significant difference test: $P > 0.05$). Classes A and G are statistically indistinguishable in terms of HDI ($P = 0.93$), standard of living ($P = 1.00$), life expectancy ($P = 0.83$), and literacy ($P = 0.12$). All data are from the year 2000.

values were substantially lower and statistically indistinguishable from each other ($P > 0.9$) (Fig. 1A). These results are robust to the particular thresholds used to define the frontier classes (*13*) (figs. S2 and S3). A boom-and-bust pattern is also found for each of the HDI subindices: standard of living, literacy, and life expectancy (Fig. 2, B to D).

Our analysis investigated relative development patterns across space, rather than the trajectory of absolute development through time. The latter was not possible given a lack of long-term time-series data, but the former has the advantage of standardizing for temporal changes that affect the entire region (e.g., economic cycles in the Brazilian economy). Hence, the boom-and-bust pattern we report does not necessarily imply that the absolute HDI of individual municipalities has first increased and then declined as deforestation has progressed; given Brazil's overall improvement in HDI over time (e.g., median municipality HDI increased from 0.627 in 1990 to 0.713 in 2000) (*8*), it is likely that development levels have generally increased throughout the Amazon. What our results suggest is that life expectancy, literacy, and standard of living improve more quickly than the national average in municipalities at the early stages of the deforestation frontier, and at below-average rates as deforestation progresses, resulting in relative HDI values that are higher at the frontier, but lower and similar in pre- and postfrontier municipalities (fig. S4).

The immediate causes of most deforestation in the Brazilian Amazon are the expansion of mechanized agriculture and land use changes by newly arrived migrants (*15*, *16*) (fig. S5). A wide diversity of people migrate to the frontier (including capitalized ranchers and farmers, colonists, landless peasants, gold miners, loggers, and landgrabbers) (*17*), but ultimately they are all attracted by the prospect of life improvement. The increase in HDI suggests that such improvement does take place at the early stages of the frontier (Fig. 2), although an alternative explanation might be that increased HDI is "imported" by immigrants coming from regions in Brazil that have better levels of education, health, and access to capital (*14*). However, immigration alone is unlikely to explain the "boom" in HDI at the early stages of deforestation, because people moving into the frontier are generally poorer and less educated than average in their areas of origin (*15*), and also because the frontier would probably not attract large-scale investment or migrants if it did not provide real prospects of high economic return and life improvement. More likely, HDI increases as people capitalize on the newly available natural resources—including land, timber, and minerals (*15*, *17*)—and on the improved accessibility to markets promoted by the new roads (*18*) that are associated with frontier expansion (*19*). Accordingly, relative levels of income improve very quickly at the early stages of deforestation (Fig. 2B). So do levels of literacy (Fig. 2C) and life expectancy (Fig. 2D), possibly because improved income and road connections result in better living conditions and improved access to education and medical care, and because governmental investment strengthens educational and medical infrastructure.

At the frontier, development levels come close to (and income even exceeds) the median values across all Brazilian municipalities. However, our results suggest that those improvements are transitory, with municipal standard of living, literacy, and life expectancy declining in the postfrontier to levels similar to those in the prefrontier municipalities (Fig. 2). This "bust" is likely to reflect the exhaustion of the natural resources that supported the initial "boom," compounded by the increasing human population. Accordingly, per capita timber (Fig. 3A), cattle (Fig. 3B), and crop production (Fig. 3C) also exhibit boom-and-bust patterns across the deforestation frontier. Timber (Fig. 3D) and cattle (Fig. 3E) also decline on a per-area basis, indicating a reduction in overall productivity irrespective of increasing human population. The first is expected, as the very resource on which timber production relies is depleted as deforestation progresses. The second likely reflects large-scale pastureland degradation as soils lose productivity (*20*), or conversion to alternative land uses as land market conditions change. By the early 1990s, more than 75% of the land that had been deforested until then in the Amazon had been used for the development of pastures, one-third of which had already been abandoned (*21*). Although the increasing population density in the postfrontier is key to understanding the decline in HDI, such density is not particularly high within the Brazilian context; most Brazilian municipalities have much higher HDI despite similar levels of population density (fig. S5).

Our results show that, in net terms, people in municipalities that have cleared their forests are not better off than those in municipalities that have not (Fig. 2). The current development pattern in the Brazilian Amazon is therefore far from desirable in terms of either human development or the conservation of natural resources. The huge challenge facing this region is how to ensure that future development paths translate into sustained improvements in human well-being, while avoiding the depletion of nature and the services it provides (*3*). A single solution is unlikely to exist. Instead, a combined approach might include supporting the better use of areas that have already been deforested (e.g., via the intensification of ranching and agriculture) alongside restricting further deforestation [e.g., through protected areas (*22*) and appropriate land use zoning (*23*)] and promoting reforestation in degraded landscapes (*24*); direct incentives to encourage forest-based livelihoods based on the sustainable harvest of timber and nontimber forest products, within and beyond forest concessions

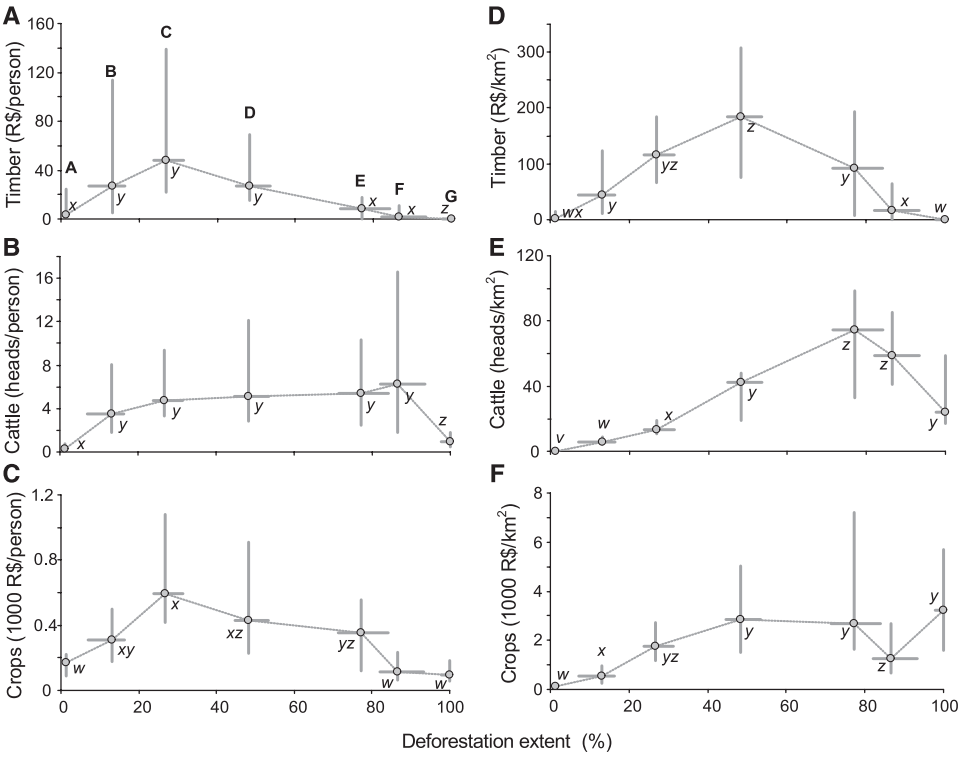

Fig. 3. Variation in the production of timber (**A** and **D**), cattle (**B** and **E**), and crops (**C** and **F**) across frontier classes A to G, either standardized by population [(A) to (C)] or by municipality area [(D) to (F)] (*10*). Timber and crop production is shown in units of Brazilian currency, the real (R$). As labeled in (A), circles from left to right correspond to classes A to G in all panels. Circles indicate median values; bars indicate first and third quartiles; horizontal dashed line indicates the median across all Brazilian municipalities. All variables present significant variation across the frontier classes (Kruskal-Wallis: $P < 0.0001$); classes that do not have a letter (*u*, *v*, *w*, *x*, *y*, *z*) in common differ significantly (Tukey's honestly significant difference test: $P > 0.05$). All data are from the year 2000.

(*25*); and targeted policies to improve literacy, health, and land tenure security (*26*).

Payments for ecosystem services, including carbon sequestration, are likely to play a key role in the financial sustainability of these approaches, by converting at least some of the wider value of Amazonian forests into local economic incentives for their long-term conservation (*27*). Such schemes are starting to be implemented in Brazil at the national (Bolsa Amazônia) and state levels (Bolsa Floresta; State of Amazonas) (*28*). Internationally, a global financial mechanism to reduce emissions from deforestation and forest degradation in developing countries is currently being negotiated under the United Nations Framework Convention on Climate Change (*7*, *29*, *30*). Brazil, with its huge carbon stocks (*31*), high technical capacity for monitoring forest changes (*32*), and improving governance (*33*), is arguably the best-positioned country for implementing and benefiting from this major new initiative. However, the long-term success of these incentives will also depend on other regional development policies, such as government incentives for agricultural expansion. For example, Amazonian "critical municipalities" with high deforestation rates now have reduced access to subsidized rural credit until targets for land tenure regularization and deforestation control are reached (*23*). Hence, although our results indicate that past development in the Brazilian Amazon has followed a boom-and-bust trajectory, future development may very well be associated with improvement in environmental quality and forest recuperation, as predicted by the environmental Kuznets hypothesis (*34*) and forest transition theory (*35*). New financial mechanisms and policies are paving the way for more sustained development trajectories and creating the conditions in which the largest tropical forest in the world can be recognized as more valuable standing than felled.

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Materials and Methods
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Editor's Summary

Boom and Bust

The Brazilian Amazon is renowned for its biodiversity and for its influence on climate regulation and geochemical cycles. It is also one of the country's poorest regions. For decades, much economic development has been pursued through conversion of forest for agriculture and cattle-ranching. **Rodrigues *et al.*** (p. 1435) investigated whether this pattern of land use brings lasting prosperity by analyzing data on the economic development of nearly 300 municipalities across the deforestation frontier. Relative development, in terms of life expectancy, literacy, and standard of living, increases as deforestation begins but then declines again as the frontier passes through. As a result, pre- and postfrontier levels of development are similarly low, indicating a pattern of boom and bust.

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