TROPICAL FOREST

Long-term forest degradation surpasses deforestation in the Brazilian Amazon

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Although deforestation rates in the Brazilian Amazon are well known, the extent of the area affected by forest degradation is a notable data gap, with implications for conservation biology, carbon cycle science, and international policy. We generated a long-term spatially quantified assessment of forest degradation for the entire Brazilian Amazon from 1992 to 2014. We measured and mapped the full range of activities that degrade forests and evaluated the relationship with deforestation. From 1992 to 2014, the total area of degraded forest was 337,427 square kilometers (km^2), compared with 308,311 km^2 that were deforested. Forest degradation is a separate and increasing form of forest disturbance, and the area affected is now greater than that due to deforestation.

Several international initiatives—such as the Aichi Biodiversity Targets in the Convention on Biological Diversity, REDD+ (Reducing Emissions from Deforestation and Forest Degradation) in the United Nations Convention on Climate Change, and the Bonn Challenge, which focuses on restoration of degraded forests—require information on the rate and extent of forest degradation (*1*, *2*). Yet, degradation of forest ecosystems is perhaps one of the more challenging types of disturbances to measure and monitor. The rate and extent of forest degradation in the Brazilian Amazon (BA) is a key component of a national strategy for climate change mitigation and adaptation (*3*). One challenge with monitoring degradation is that it occurs within forests, leaving a standing stock of biomass and canopy cover that can make detection difficult. Forest degradation in the BA and elsewhere is caused by an array of agents or drivers, with greater or lesser degrees of poorly quantified interaction between drivers or with deforestation activities. Unlike deforestation, degradation events may reoccur with varying frequencies at the same location, sometimes several years later, and different types can spatially overlap.

Fundamentally, forest degradation has been widely recognized as an important form of disturbance (*4*–*6*). However, previous efforts to measure and map degradation in the BA have focused on individual agents, such as logging (*7*), burned areas or active fires (*8*, *9*), or fragmentation (*10*). Others have assessed degradation only indirectly; for instance, Baccini *et al.* (*4*) estimated carbon emissions from degradation as the difference between overall canopy damage and that attributed directly to deforestation (*11*). Other analyses have focused on specific sites or subregions (*5*) or on sampling in forest strata spatially associated with concentrated deforestation (*12*). In this analysis, our aim was to map the current BA-wide extent of forest ecosystems that have been degraded since 1992 and compare it with the area deforested. The analysis presented is a long-term (~23 years) BA-wide high-resolution spatial analysis, intended to reveal how degradation has changed in magnitude and geographic distribution and to measure its permanence in the landscape.

Forest disturbance by human activities in the BA occurs across a gradient of severity, from complete forest conversion to various intensities of degradation within forests. Deforestation is the complete conversion of forests to another land use type, usually pasture in the BA. Forest degradation occurs within forests and is characterized by a loss of biomass within an intact canopy (*6*). Forest degradation is also a secondary result of deforestation, which produces edge effects and isolated forest patches in fragmented forests (*13*). These disturbances have important large-scale environmental consequences, including the release of greenhouse gases (*14*–*16*), alteration of water and energy balances (*17*, *18*), loss of biodiversity (*19*, *20*), and increasing incidence of infectious disease (*21*). In the BA, deforestation reached a peak rate in 2003 to 2004 at ~29,000 km^2 $year^{-1}$, bringing international attention and then national policies that reduced these rates significantly (*22*). By 2014, deforestation rates declined below ~6000 km^2 $year^{-1}$ based on satellite data analysis by the Amazon Deforestation Monitoring Project (PRODES) operated by the Brazilian Space Agency, Instituto Nacional de Pesquisas Espaciais (INPE) (*23*).

To map and analyze the distribution and extent of degraded forest in the BA forest landscape, we needed to use medium-resolution remote-sensing (30 m) data. An existing model (*24*–*28*) uses a stepwise semiautomated analysis of all Landsat images for the forest area of the Legal Amazon of Brazil (*29*). We mapped six types of forest disturbance: (i) deforestation, (ii) selective logging, (iii) understory fires in intact forests, (iv) fires on logged sites, (v) forest edge effects adjacent to deforested areas, and (vi) isolated forest fragments created by deforestation. The method (*29*) uses a visual digital object analysis framework, digital spectral analysis (canopy texture from spectral radiance variation and canopy density from spectral mixture analysis), and then iterative calibration using field data (*26*–*28*). A dataset was constructed from more than 1200 Landsat satellite digital images covering the entire BA forest area, which were then digitally analyzed for seven observation years (OYs): 1992, 1996, 1999, 2003, 2006, 2010, and 2014. The six digital map layers were stacked at each OY to delineate pixel overlay unions of new occurrences, persistent occurrences, overlapping occurrences, and sequential occurrences (figs. S1 to S3).

Digital spatial data layers for deforestation were obtained from INPE's long-term PRODES dataset (*23*) for overlay with degradation layers in OYs after 2000 through 2018. For deforestation mapping before 2000, we processed data as reported in (*24*) and (*26*). The INPE deforestation dataset is the official national reporting source and provides a logical benchmark for comparing our estimates and maps of degradation. We developed and field-validated a periodic measurement model that produces accurate estimates of logging and burned area every 3 to 4 years for moderate- and high-intensity logging of removals of >10 m^3 ha^{-1} (*24*, *27*, *29*, *30*). Forest edges are mapped only in undisturbed forest adjacent to deforested areas to 120 m. Edge areas adjacent to logging or burned scars are not counted in the edge counts. Isolated forests created by deforestation are mapped for all undisturbed forest patches between 1 and 100 km^2 in size. To report degradation of undisturbed forest, each pixel was assigned a single identifier according to a hierarchical rule (table S1). This excluded double counting of degradation occurring multiple times on a single pixel of land, but the combinations and recurrences are retained in the database.

Average annual rates of new degradation are presented in Fig. 1A, compared with the rate of deforestation. These were derived from mapping the remote sensing–detected degradation at each OY and new degradation between each OY (tables S2 and S3). As expected, overall degradation declined with deforestation rates and a concomitant decline in production of edge and isolated forest fragments, which make up a large fraction of all degradation during the early period. Declining deforestation resulting from new policy measures

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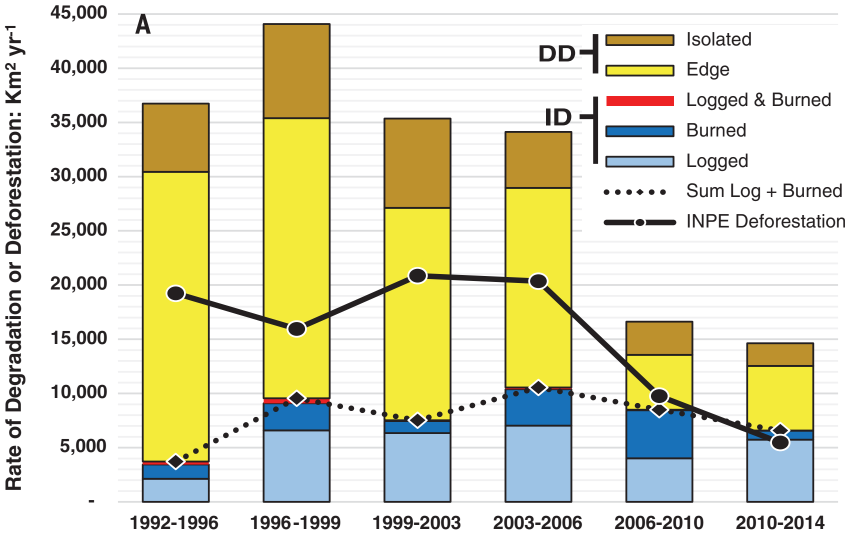

B

Forest disturbance	Area $(km)^2$
Logged forest	98,542
Burned forest	33,476
L + B forest	1,672
Edges not L or B	129,163
Isolated not L or B or E	74,574
Degraded, 1992-2014	337,427
Deforested, 1992-2014	308,311

Fig. 1. Quantitative results of forest degradation in the BA, 1992 to 2014. (**A**) Annual average rates of forest degradation; total and contributions from each type are shown as segmented bars, with the rates of logging and understory burned areas shown by the dashed line and rates of deforestation from INPE by the solid line. DD, dependent degradation types; ID, independent degradation types. (**B**) The cumulative area impact of forest degradation on the forest biome landscape in the BA by each type of degradation and comparison with the total area deforested during the analysis period, 1992 to 2014.

reduced new edges and isolated forest after 2006 to 2010, but edges began to decline earlier while deforestation remained high, most likely as a result of consolidation and fill-in of spatially dense and continuous deforested areas. Overall, the annual rate of all types of degradation declined over the time series, from a peak of 44,075 to 14,625 km^2 $year^{-1}$. Nonetheless, forest degradation rates exceeded deforestation by almost threefold in 2014.

Whereas rates of fragmentation decreased, rates of selective logging and understory burning, two types of heavy-impact forest degradation, slightly increased or remained stable over time. The amount of new selective logging created between 1992 and 1996 increased from 8,498 to 22,952 km^2 between 2010 and 2014, an increase of 270% (table S3). When combined with new burned forest, the area increases from 14,866 km^2 in 1992 to 1996 to 26,327 km^2 in 2010 to 2014, an increase of 177%. By 2006 to 2010, the average annual rates of forest degradation by logging and burning were approximately equal to deforestation rates, and by 2014 degradation exceeded deforestation (Fig. 1A).

To compare the amount of degraded forest in the BA today with the deforested area, all newly created degradation pixels were tracked and accumulated through time. There was no double counting of more than one type of degradation occurring at the same place, and pixels that were deforested by 2014 were removed (Fig. 1B). The total degraded forest created during the period of our analysis and that remain present in the current landscape is 337,427 km^2, compared with 308,311 km^2 of deforested land. This estimate does not include degradation that occurred before 1992. Much of the degradation was from edges and isolated forest fragments, but the total area degraded by logging and burning alone over this period was equivalent to almost half (43%) of the area deforested over this period. In most locations across the BA, there is more degraded forest than deforested land when considering only what occurred during the time frame of analysis (fig. S4). During this long-term period of observation, 40% of all degraded forest can be attributed to intensive logging and understory fires and 60% is due to edges and isolated fragments of forest, which represents a notable increase in the logged and burned fraction later in the record.

BA-wide estimates from the analysis were constructed at the original 30-m resolution and then aggregated in 200-km^2 grid cells for mapping and graphical display (Fig. 2). These maps show the cumulative impact of all degradation types. The map shows the status of forest ecosystems in the BA, including the density and extent of degradation. The mapping is presented for the entire period of analysis and separately for the period before the downturn in deforestation rates and the period after. Generally, degradation is more spatially dispersed across the landscape than deforestation, which is concentrated in the often-cited "arc of deforestation" along the eastern and southern forest interface with the Cerrado Biome in Brazil, which comprises a region with vegetation types similar to African savannah. There are concentrated zones of high degradation close to older areas of deforestation, but degradation is also emerging in the western BA, particularly by new logging (Fig. 3). The spatial organization of logging suggests that it is increasingly decoupled from understory burning (figs. S5 and S6), where logging is relocating more distantly from the so-called arc of deforestation, whereas burned areas remain more restricted closer to the older areas of deforestation (figs. S7 and S8). Furthermore, we found very little overlap of burned areas on logged areas, especially in the short term (4 to 8 years).

The dominant local driver of degradation was mapped for each 200-km^2 grid cell (Fig. 4). Degradation related to deforestation, such as edges and isolated fragments, is important in the BA-wide landscape, not only in the older areas but also along the new frontiers. Logged areas are dominant in some specific areas where degradation is uniformly very high, and they are expanding to the west along a new frontier (Fig. 4 and figs. S7 to S9), whereas nodes of burned dominance are very spatially localized. Edge and isolated forest fragments are spatially and geographically extensive. Edges tend to be the prevalent and extensive type in the earliest years and then in the new frontier of western BA (Fig. 4, B and C), whereas isolated forest dominates some old areas of deforestation and degradation during the later years (Fig. 4C). In most places, all types of degradation are occurring in the landscape, although we found little evidence of significant spatial overlap and co-occurrence, even when considering degradation co-occurrences widely separated in time.

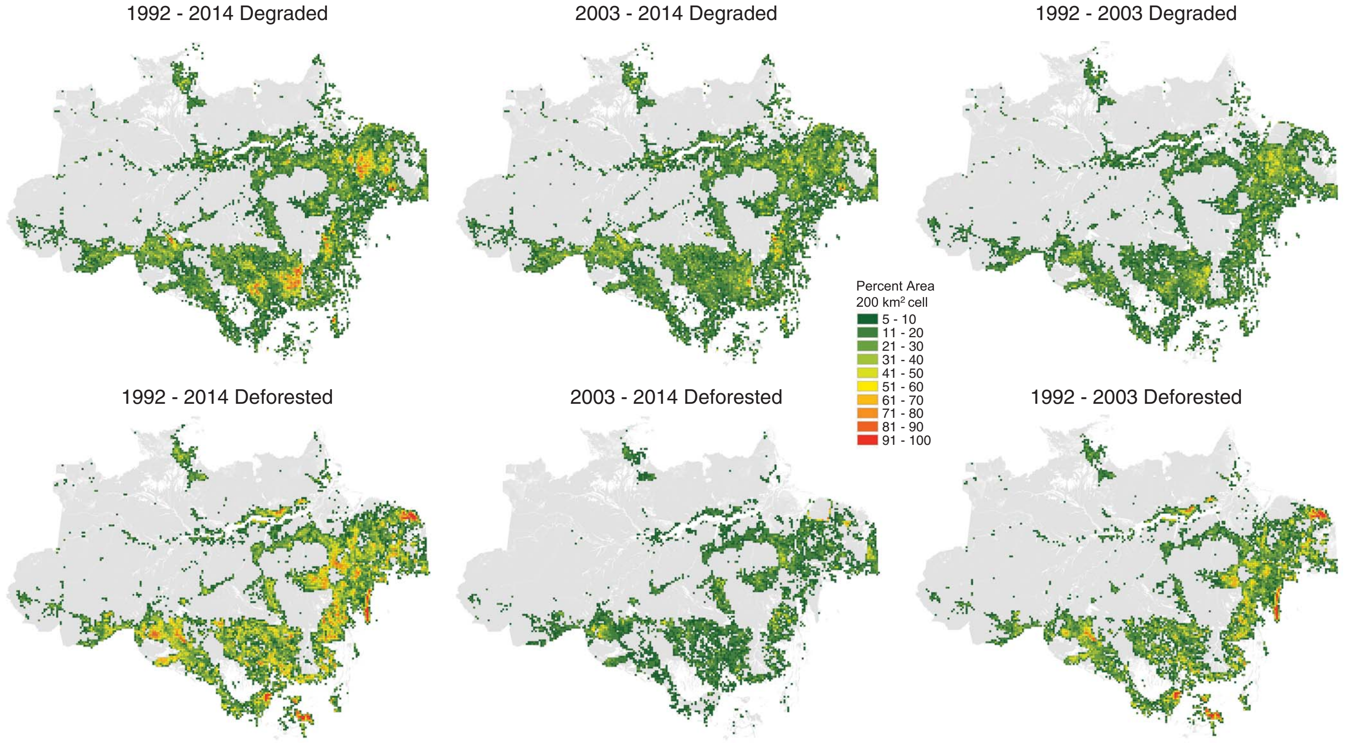

Fig. 2. Spatial mapping of forest degradation in BA forest ecosystems. The maps present separately the inventory of all forest areas degraded by all degradation (top) not deforested, compared with the total deforested land (bottom), between 1992 and 2014. Maps on the left show all degradation or deforestation during the study period. Center maps show degraded forest or deforested areas after the downturn in deforestation rates. Maps on the right show areas degraded or deforested before the downturn in deforestation. The amount of degraded forest is aggregated into 200-km^2 grid cells and represented as the fraction (percentage) of the cell.

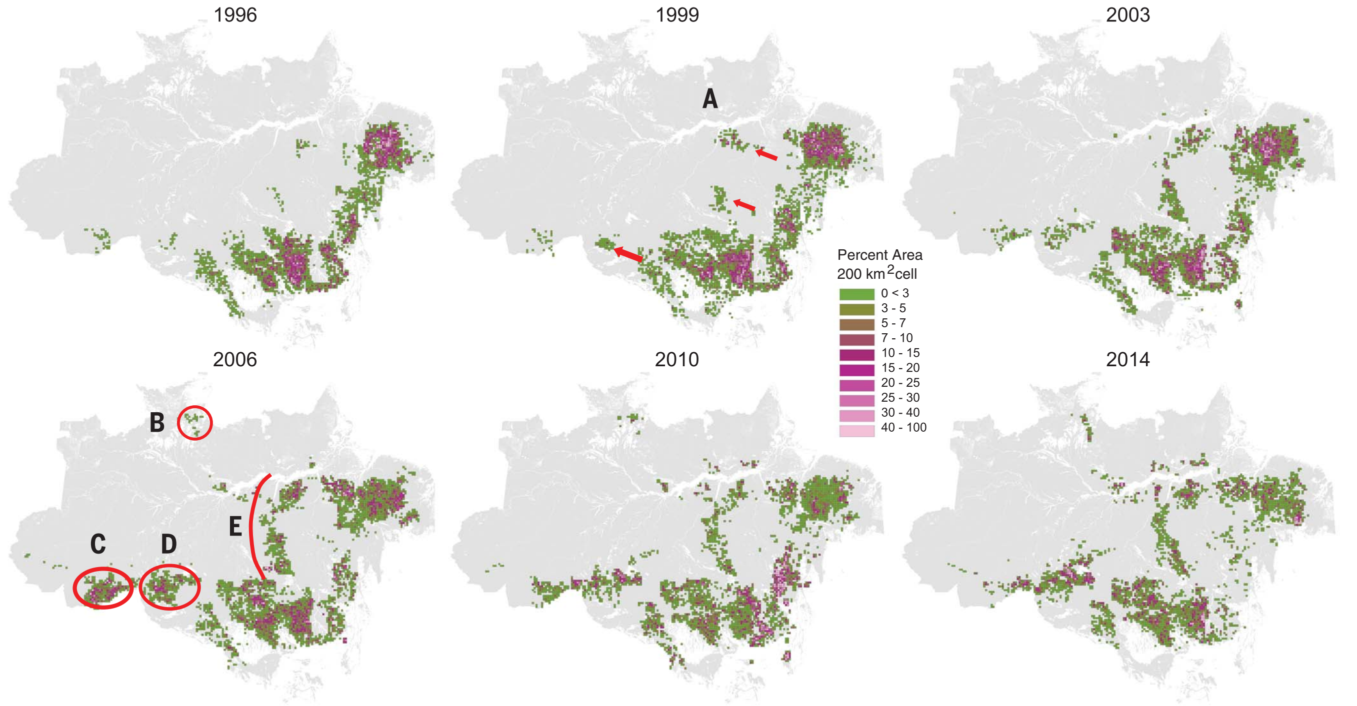

Fig. 3. Detected areas of forest degradation by logging and understory burning at each OY. Areas are mapped as a fraction of a 200-km^2 grid cell for the entire BA. The geography of logging is shown to have expanded from the older deforestation zone, often cited as the arc of deforestation, particularly after 2003. (**A**) Arrows show the general direction of the expanding logging frontier. (**B**) New distant forest degradation in Roraima. (**C** and **D**) New forest degradation from logging in the western Amazon. (**E**) The prominent forest degradation front in western Pará.

Results from an analysis of regional trends were surprising (figs. S7 to S9). New logging areas are demonstrably expanding beyond the older arc of deforestation into a new western frontier (Fig. 3 and fig. S7), but spatiotemporal trends for other types are less clear. Understory burned areas remain predominant in the specific areas of concentrated deforestation, with temporal trends somewhat intermediary or stable, having increased in the early period of record and now declining with deforestation rates. Interestingly, creation of new edges and new isolated forest fragments has generally declined over the entire record, particularly as deforestation rates have declined, although their coverage area remains high in overall magnitude. In fact, areas with highest overall coverage and density are also experiencing declining rates, regardless of type. The new frontiers with high and increasing rates are still quantitatively low in magnitude. The highest densities of degradation are along the long-standing deforestation frontier but present declining trajectories, whereas the emerging frontiers with lower densities have increasing trajectories; these new and expanding regions will likely be dominant in the future.

For degradation to be an important form of forest disturbance in the BA, it must persist in the landscape and not be immediately converted by deforestation. We spatially tracked at the 30-m pixel scale the survivorship of each cohort of new degraded forest through the time series (table S7 and fig. S10). Survivorship is measured as the area and percentage of a cohort of degraded forests that persists without being deforested for a given length of time. Logged areas persisted the longest, as more than half (57%) of the area survived at least 18 years, from 1996 to 2014 (46% from 1996 survived to 2018). Fully one-third of logged areas in 1992 were still present in the 2018 landscape, some of which had been relogged. The other types of degradation had much lower 18-year survivorship by 2014, ranging from 28 to 31%. Interestingly, as much as one-third of logged areas from 1992 were still present in 2018, and one-fifth to one-fourth of the other types of degradation in 1992 were still present in 2018. Through the time series, survivorship was generally consistent but slightly increased after 2003, when deforestation rates declined. Some researchers have reported very low survivorship of logged areas for short periods of up to 4 years (*31*), but we found high short-term survivorship for all types of degradation in general but especially for logged areas, and these ranged from 82 to 93%. Burned areas have considerably lower short-term survivorship, ranging from 50% in the earlier period to 86% later in the time series, as deforestation rates declined. Edge and isolated forest short-term survivorship ranged from ~50% in the early period to ~80% later, but also increased as deforestation rates declined. Although deforestation policy did not influence logging or lead to a decline in burned area degradation, it did relieve conversion pressures so that these logged and burned areas now persist longer. Reduced conversion pressure has extended the persistence of edges and isolated forest, which exacerbates tree mortality and other ecological effects (fig. S10).

A large spatial overlay analysis to understand the co-occurrence of the different types of degradation follows naturally from the persistence analysis. We examined overlays of all degraded forest that were not deforested through 2014. The results were somewhat unexpected, in that spatial co-occurrence of different degradation factors is very low. Throughout the BA, it is common to have all four types of degradation occur, but there is no evidence that they overlap in any significant way, a finding that has implications for degradation intensity and our understanding of the interaction between drivers. Of all degraded forest in the current landscape, 90% has been degraded by only one factor (table S9).

This analysis considered the density, dominance, direction, and duration of five types

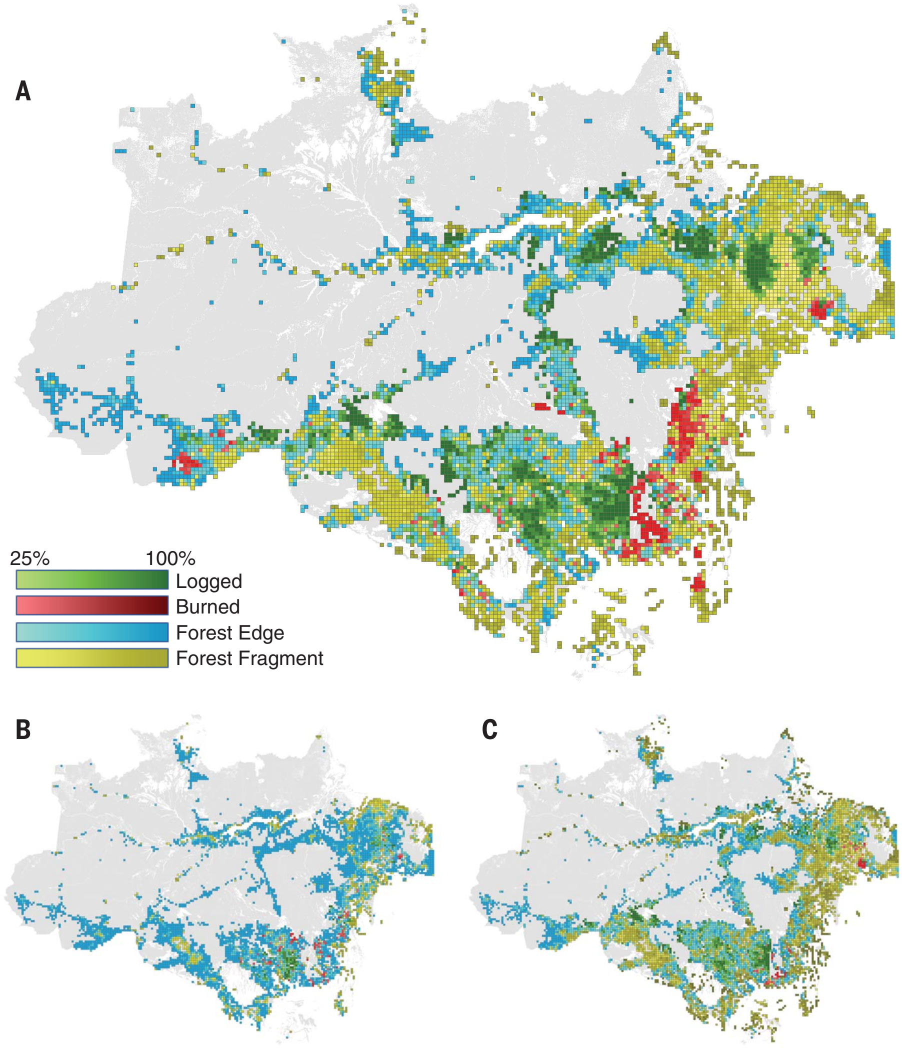

Fig. 4. Maps of dominant drivers of degradation. Four types of degraded forest are shown: logged, understory burning, edges, and isolated forest fragments. The quantitatively most abundant type in each 200-km^2 grid cell is the dominant driver at that local level. The color represents the most dominant type, whereas the tonal gradient indicates how dominant it is compared with other types, as a percentage of all types present. If all four types existed in approximately equal magnitude, the tone would be close to 25%, whereas the color tone would be darker and closer to 100% if there was only one type present. (**A**) The overall status of dominant types cumulatively through the entire time period, 1992 to 2014. (**B**) The dominant type at the start of the period of analysis, observed in 1992. (**C**) The dominant type at the end of the period of analysis, observed in 2014.

of forest degradation over almost three decades. Edge effects and isolated forest fragments have been substantial contributors to the current degraded state of forest over the record, but the fragmentation contribution is declining while overt degradation from logging, and to a lesser degree fire, is becoming more prominent. We observed that there has been a transition from a deforestation-mediated fragmentation regime to one with an elevated importance of new logging and fire, which is geographically shifting to a new western "degradation frontier." We can articulate a simple framework for understanding these dynamics by considering two broad categories of forest degradation types: (i) those that are dependent on, or coupled to, deforestation, such as the fragmentation effects of edges and isolated fragments (DD); and (ii) those that are more independent of, or decoupled from, deforestation, such as logging and to a lesser degree understory fire (ID).

National policies in Brazil have been established in a command-and-control fashion to reduce the rate of deforestation, and they have been effective. In turn, such deforestation policies have influenced rates of DD forest degradation. However, these policies have had minimal effect on curbing ID degradation and have led to more persistent and long-lasting ID degradation in the landscape. Furthermore, annual rates of ID degradation now exceed deforestation rates, while being geographically dispersed to new frontiers not associated with the historical deforestation frontier along the so-called arc of deforestation. With either the current policy situation or a return to laissez faire policies that ignore degradation generally and ID degradation specifically, the rate and extent of forest degradation will likely increase in the future in response to market forces and the establishment of a separate logging sector infrastructure for extraction, processing, and transport. Selective logging has always been one of the first entryways into undisturbed forests, as it occurs within close proximity of existing settlement and clearing. Now, logging is demonstrating the potential to leap further distances into remote areas.

Several of our analytical assumptions and methodological features suggest that our estimates are conservative. Our buffer distance for edges is 120 m, and we did not estimate edges around logged and burned areas. Our logging detection does not include very-low-intensity logging below 10 m^3 ha^{-1}, so it may omit some cases of reduced-impact logging. We also did not include highly selective individual tree logging, which occurs in the process of deforestation or tree removals by individual farmers on their homesteads, or indigenous logging. The periodic use of OYs may miss some low-intensity logging or small burning events. Inclusion of these factors would only increase the estimate of how much degradation exists in the landscape today.

The overall conclusion from this work is that forest degradation is a significant form of landscape and ecosystem disturbance. Degradation in the BA is a persistent form of disturbance, not simply one that is eventually replaced by deforestation. Focusing attention on deforestation alone ignores an additional area of forest degraded by selective logging, understory fire, edge effects, and isolation of fragments that is equal in areal extent to cleared forest.

Improved long-term spatial data on forest degradation are sought by most multilateral environmental agreements. Our analysis provides a cogent example of monitoring data needed to estimate species loss from forest fragmentation and degradation, which is a key element of Target 5 of the United Nations Convention on Biological Diversity. Our results align with long-term ground-based studies of forest fragmentation in conservation biology (*32*, *33*) and contribute to a better understanding of species biodiversity loss (*34*, *35*). Our measurements reemphasize the importance of technical consideration of forest degradation in the international dialog on REDD+, for which most monitoring has been focused on deforestation.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S11
Tables S1 to S9
References (*36*–*45*)

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Degradation exceeds deforestation

Forest degradation is a ubiquitous form of human disturbance of the forest landscape. Activities such as selective logging and extraction fall short of total deforestation but lead to loss of biomass and/or fragmentation. On the basis of remote sensing data at 30-meter spatial resolution, Matricardi *et al.* analyzed the extent of forest degradation across the entire Brazilian Amazon over a ~22-year period up to 2014. They found that the extent and rate of forest degradation was equal to or greater than deforestation, which has important implications for carbon, biodiversity, and energy balance.

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