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The Incidence of Fire in Amazonian Forests with Implications for REDD

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Reducing emissions from deforestation and degradation (REDD) may curb carbon emissions, but the consequences for fire hazard are poorly understood. By analyzing satellite-derived deforestation and fire data from the Brazilian Amazon, we show that fire occurrence has increased in 59% of the area that has experienced reduced deforestation rates. Differences in fire frequencies across two land-use gradients reveal that fire-free land-management can substantially reduce fire incidence by as much as 69%. If sustainable fire-free land-management of deforested areas is not adopted in the REDD mechanism, then the carbon savings achieved by avoiding deforestation may be partially negated by increased emissions from fires.

Reducing emissions from deforestation and degradation (REDD) is one of the most cost-effective mitigation mechanisms (*1*) and could contribute to an emission reduction of 13 to 50 billion tons of carbon (Gt C) by 2100 (*2*). REDD is therefore a high-priority mechanism for mitigation of climate change within the United Nations Framework Convention on Climate Change (UNFCCC). The future of REDD implementation relies on forthcoming agreements to tackle the unresolved outcomes from the 15th Convention of the Parties, which took place in December 2009. These negotiations can largely influence the maintenance or replacement of the Kyoto Protocol beyond 2012 and the future of tropical forests. Policy-makers are considering a range of options for developing countries to receive financial incentives to reduce their deforestation rates (*2*). However, the efficacy of REDD as a climate change mitigation strategy depends, in particular, upon the stabilization of deforestation and degradation of the world's largest rainforest, the Amazon.

Deforestation in the Brazilian Amazon (defined as clear cutting and conversion of the original forest cover to other land uses) has resulted in annual forest area loss of 18,918 ± 1,576 km^2 (SEM) from 1998 to 2007, according to the National Institute for Space Research (INPE) in Brazil (*3*). It is estimated that this results in release of 0.28 (0.17 to 0.49) Gt C to the atmosphere annually (*4*), corresponding to 24% of the world's C emissions from land cover change [1.15 (0.58-1.79) Gt C $year^{-1}$] (*5*). In principle, discontinuing ongoing deforestation through mechanisms such as REDD would protect a large fraction of the 86 Gt of the carbon stored in Amazonian forest biomass (*6*), which is equivalent to about a decade of global fossil fuel emissions to the atmosphere. However, there is a pressing need to consider the threat to forests posed by fire.

Fires following drought years are likely to release a similar amount of carbon as emissions from deliberate deforestation (*7*, *8*). The combined effect of deliberate deforestation and forest fires has a similar magnitude to the natural annual carbon sink of 0.45 (0.3 to 0.6) Gt C estimated for undisturbed Amazonian forests (*9*). The higher probability of a drier Amazon in the 21st century predicted by some global circulation models (*10*, *11*), and consequent increasing drought intensity and frequency, may push Amazonia toward an amplified fire-prone system (*12*). Previous studies (*13*, *14*) have shown an increase in fire occurrence following two large-scale Amazonian droughts (1998 and 2005). Changes in fire frequency could jeopardize the benefits achieved through REDD; however, despite its vital importance in this region, fire is currently neglected in the emerging UN framework.

Operational satellite-derived deforestation (*3*) and fire (*15*) data sets produced by INPE, and land cover information from the European Commission's Joint Research Centre (*16*), provide a unique opportunity to quantify the sensitivity of fires to changes in deforestation rates and land use in the Brazilian Amazon. Fire in the Brazilian Amazon is likely to follow three plausible pathways: (i) Fire incidence may decrease with reduced deforestation rates by restraining human activities that are major ignition sources (*8*, *13*, *14*, *17*). (ii) It may increase even with reduced deforestation rates, both through slashing and burning of secondary forests (*18*) in already deforested areas that are not monitored by INPE's Program for Deforestation Assessment in the Brazilian Legal Amazonia (PRODES) (*19*) and through continuous enlargement of forest edges (*20*) and increasing area of secondary forest cover (*21*) that are more susceptible to fire (*22*). (iii) Fire incidence may decrease because of a shift from extensive (unmanaged) to intensive (managed) land-use methods, as the latter is normally not accompanied by deliberate use of fire (*23*).

To distinguish the first two pathways we used all available regionwide data from INPE to perform a pixel-based analysis of temporal trends in deforestation rates and fire incidence (*19*). For each pixel at 0.25° by 0.25° (or 774.35 km^2) spatial resolution, the annual fraction deforested for the period from 2000 to 2007 was derived by aggregating the 60-m spatial resolution pixels from INPE's PRODES annual deforestation maps (*3*, *19*). Similarly, the annual number of fires for each 0.25° by 0.25° pixel for the period from 1998 to 2006 was derived (*19*) by aggregating the daily

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1-km spatial resolution active fire detections from the advanced very high resolution radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration NOAA-12 satellite produced by the INPES's fire monitoring system (*15*). For each pixel and for each data set, we computed the slope of the temporal trend regression line and the confidence level according to the two-tailed Student's *t* distribution (*19*). Finally, we analyzed the frequency distributions of pixel-based fire trends associated with positive and negative deforestation trends, in order to evaluate whether fire incidence was increasing or decreasing in each of the two deforestation categories (*19*).

The temporal trend analysis on the deforestation data revealed a widespread pattern of grid cells with negative slopes (54% negative against only 17% with positive slopes), indicating that deforestation rates have been decreasing in most of the Brazilian Amazon from 2000 to 2007 (Fig. 1A). Because of the overall unimodal "boom-and-bust" nature of deforestation rates (fig. S2) during the time period analyzed (*24*, *25*), in only 4.7% of grid cells with negative slopes and 10% of grid cells with positive slopes were the trends significant at a 90% confidence level (two-tailed Student's *t* distribution, $t < 1.94$, df = 8 years – 2) (Fig. 1A).

Fires, on the other hand, follow a reverse pattern to deforestation with the number of grid cells with positive slopes (42%) 1.7 times those of cells with negative slopes (25%). Applying a 90% confidence level according to the two-tailed Student's *t* distribution ($t < 1.89$, df = 9 years – 2), our results show that in almost 30% of grid cells with an increasing fire trend [an area ~2.6 times larger than the U.K. (625,675 km^2)], there is a statistically significant increase in fire incidence, whereas only 10% of the cells with a reducing fire trend have experienced a statistically significant decrease in fire incidence (Fig. 1B). The most drastic ($t < 2.365$, $P < 0.05$) increases in fire activity were observed in the southwest and central portions of Pará state, northwest of Mato Grosso state, north of Rondônia and Maranhão states (Fig. 1B).

By combining deforestation and fire trend results (excluding all grid cells with null slope), we were able to analyze the behavior of fire incidence in areas with increased and decreased deforestation rates (*19*). Most grid cells with increased deforestation rates (81%, positive regression slopes) are overlapped by grid cells with positive fire trends (Fig. 2, A and B), which confirms the expectation that fire occurrence increases with deforestation (*17*). Much more surprisingly, though, most of the grid cells (59%) with decreased deforestation rates (negative regression slopes) also show increased fire frequency (Fig. 2, A and B). These results were also confirmed by using the 2000 to 2006 time series for both AVHRR hot pixels and PRODES deforestation rates, as well as by using Moderate Resolution Imaging Spectroradiometer (MODIS) fire data instead of AVHRR (*19*). These findings suggest that, over 31% of the study area, the pattern is more consistent with increased fire frequency despite reduced deforestation—although, over 13% of the area, the trend is consistent with increased fire with deforestation.

The trends observed here may emerge because there is a culturally widespread use of fire to manage land in Amazonia. Slash-and-burn treatment of secondary forests is a common practice in Amazonia that shifts cultivation to restore soil properties and to reutilize the land. Secondary forest deforestation is not monitored by the PRODES system (*19*) (fig. S3) and, hence, is a plausible explanation of the reverse trend observed between deforestation and fire. Furthermore, reducing deforestation rates slows, but does not prevent, the continuous expansion of the cumulative area deforested. This leads to a permanent enlargement of forest edges (*20*) and secondary forest cover (*21*), which are more susceptible to fire (*22*). Forest landscapes in Amazonia are

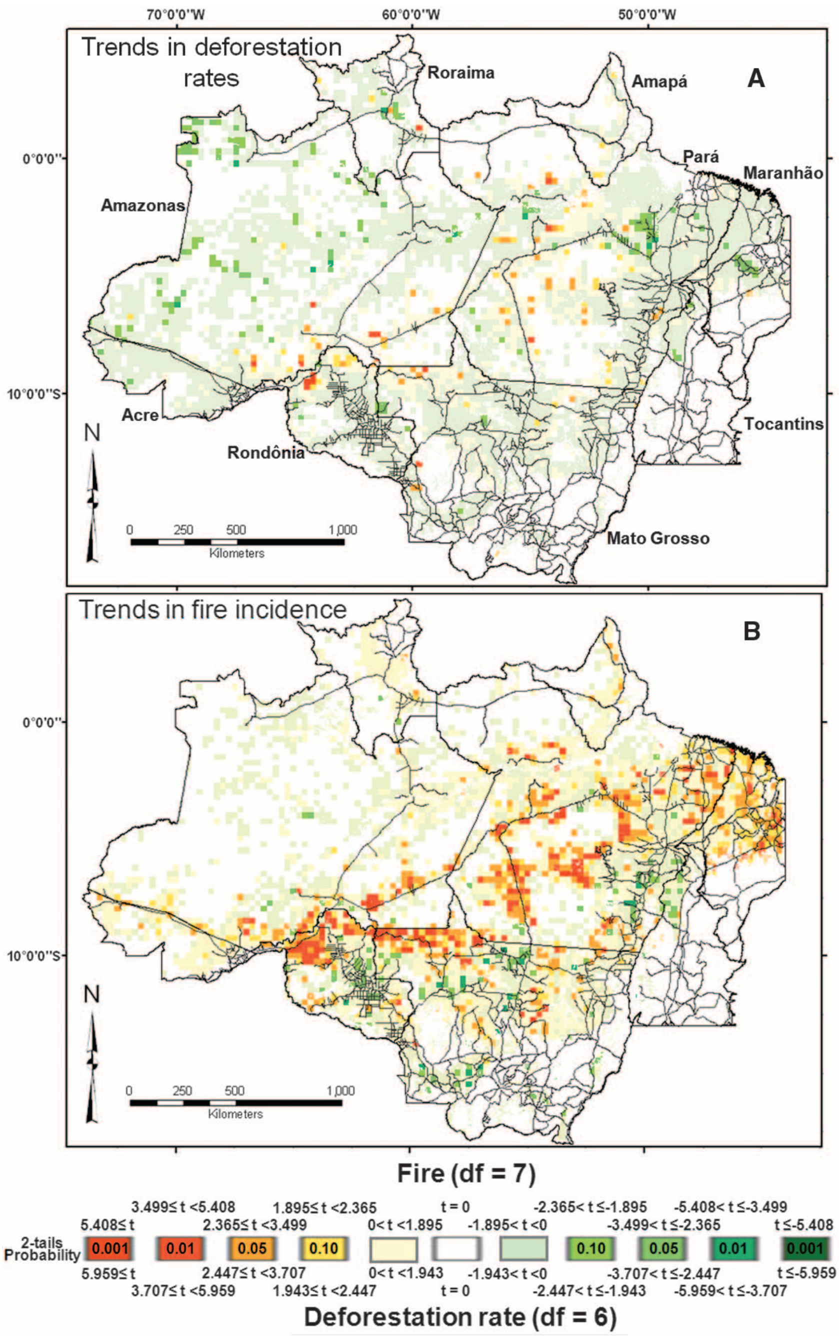

Fig. 1. Maps showing the significance of the trend regression slopes based on the two-tailed Student's *t* distribution for changes in (**A**) deforestation rates and (**B**) fire incidence over the time periods analyzed. From yellow to red, slopes are positive, which indicates an increase in deforestation rates or fire incidence. From light to dark green, slopes are negative, which indicates a reduction in deforestation rates or fire incidence. Different colors indicate the level of significance of the regression trend.

becoming more fragmented (*20*), and therefore, a growing proportion of forests is exposed to the leakage of accidental fires from adjacent farms, which could cause an increase in future fire susceptibility, fuel loading, and fire intensity in these areas (*26*). Furthermore, this effect is likely to catalyze a perhaps irreversible cascade of biodiversity loss by complete turnover of species composition (*27*), which affects the functioning and ecology of this biome, with a consequent increase in carbon emissions to the atmosphere (*28*).

REDD may therefore succeed in curtailing the clearing of large original forest areas for cattle production and mechanized agriculture, which have been the foremost drivers of deforestation rates in Amazonia (*29*). However, although the monitored deforestation rates may be reduced, fires and the associated carbon emissions may continue to increase because of cryptic land-use processes. So how can the patterns observed here be reversed?

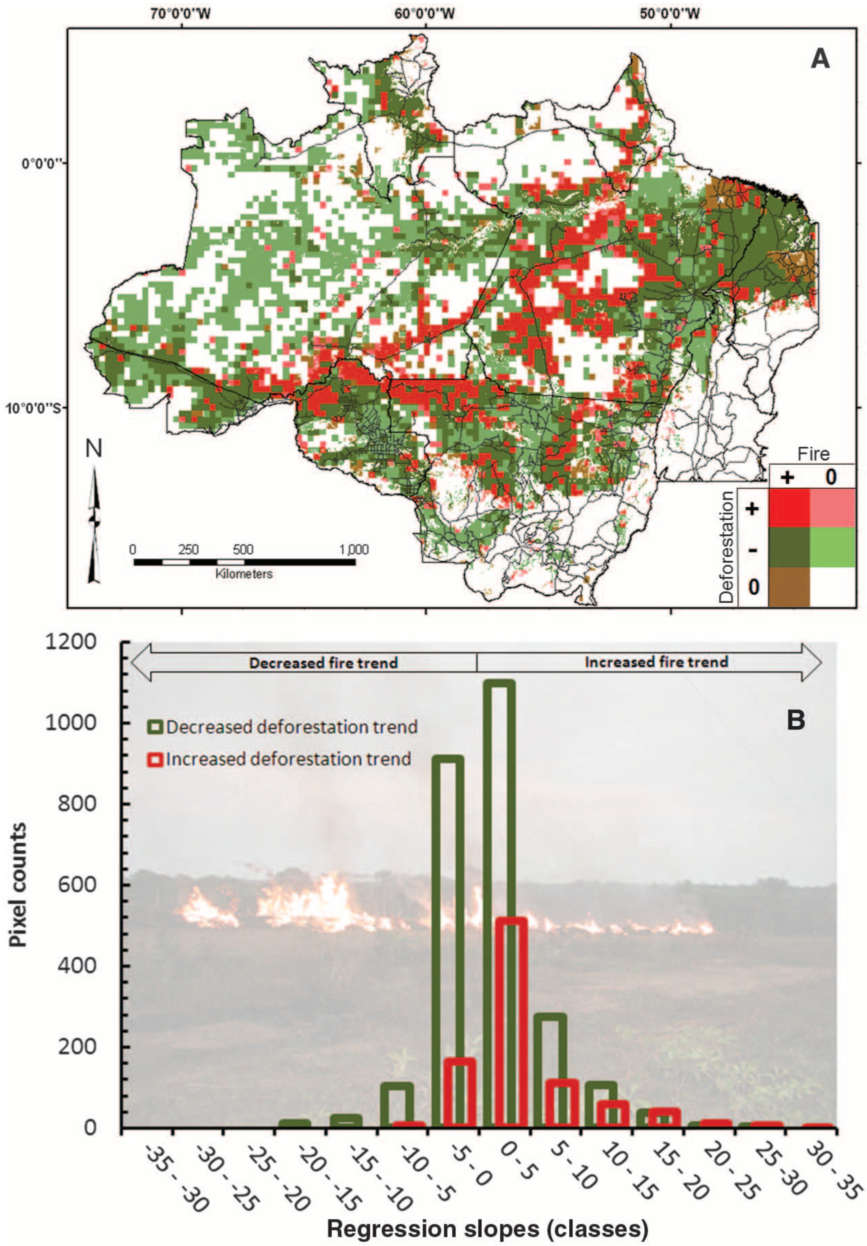

Fig. 2. (**A**) Pixel-based integration of the deforestation (Fig. 1A) and fire (Fig. 1B) trend surfaces obtained by using a decision rule classifier (*19*). The color board in the bottom left of the figure indicates the direction of the trends of each variable within the grid cell. Red cells indicate increased trend in both deforestation and fires; dark green cells indicate decreased deforestation rates and increased fire incidence. (**B**) The frequency distribution of these two major classes is shown; the red bars represent the frequency distribution of slopes for the trend regression applied for fire data over the areas with positive deforestation trend, and the dark green bars represent the frequency distribution of slopes for the trend regression applied for fire data over the areas with negative deforestation trend. Note that, in both cases, the histogram is skewed to the right, which indicates that the majority of grid cells have positive fire trends.

To evaluate the potential of land management in regulating fire in Amazonia (our third pathway), we used a space-for-time substitution analysis (*19*). We first created two surfaces with 0.25° spatial resolution based on the Global Land Cover 2000 map of South America (*16*): (i) the proportion of total agriculture (intensive + extensive) within each grid cell, representing the current, most common land use in Amazonia (fig. S6A), and (ii) the proportion of intensive agriculture (managed agriculture) within each grid cell, as a proxy for fire-free land management (fig. S6B). We then extracted the total number of active fire detections for the year 2000 within each grid cell and compared the evolution of fire occurrence as a function of the proportion covered by each land-use category (*19*).

It is evident that fire incidence is higher when land starts to be cleared for intensive agriculture than for total agriculture (Fig. 3). Fire frequency associated with mechanized deforestation for commercial plantations, such as soybeans, is reported to be higher than from less intensive clearing methods (*30*). Nevertheless, fire incidence becomes similar in both agricultural categories when they reach between 25 and 30% of the area of the grid cell. As intensive land use begins to dominate the landscape beyond the 35% cover threshold, we observe a constant decline in fire incidence, which reaches a maximum reduction of 69% in fire occurrence when intensive agriculture covers 85% of the grid cell area (Fig. 3). Conversely, high fire incidence is maintained with the increase in total agriculture area (Fig. 3), which is characterized by a mosaic of cropland and degraded and secondary forests (*19*). This supports our contention that a combination of slash-and-burn of secondary forests, enlargement of forest edges, and landscape fragmentation is driving fire increase in areas with reduced deforestation rates. The continuous reduction of fuel loads with the expansion of intensive agriculture could also lead to a decrease in fire incidence; however, fire is naturally rare in Amazonia (*22*), and its occurrence is strongly associated with human ignition for land management (*19*).

Two policy-relevant conclusions can be drawn here. First, focusing on the pattern of fire incidence observed between 0% and 30% of grid cell cover, ongoing expansion of agrobusiness has the potential to drive fire increase in Amazonia and must therefore be restricted in order to prevent C emissions. Second, by analyzing fire patterns on more widely farmed areas (>35% agriculture), we find that changing land-management practices in already deforested areas, by expanding the usage of fire-free methods, can drastically reduce fire activity and associated C emissions in Amazonia. The intensification of current land management in small to medium farms could, for instance, be achieved through introduction of fire-

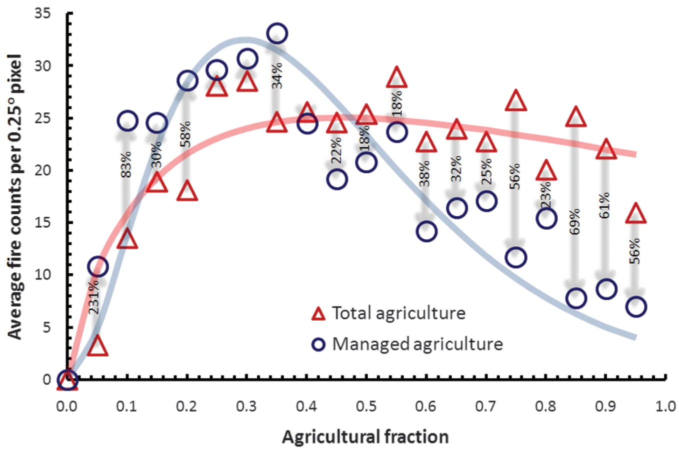

Fig. 3. Evolution of fire incidence (average number of fire counts) derived from active fire detections from the AVHRR aboard the NOAA-12 satellite produced by the INPE's fire-monitoring system (*15*) according to the fraction of area covered by intensive (managed) agriculture (blue circles) and total agriculture (extensive − unmanaged plus intensive) (red triangles) from the Global Land Cover 2000 map of South America (*16*). The relationship between fire incidence and intensive agriculture was fitted with a nonlinear function of the type $F = a[\exp(-bA_i)]A_i^2$ (blue line), where F is the average fire counts and A_i is the intensive agriculture fraction, a [2748.08 ± 332.98 (SEM)] and b [6.77 ± 0.32 (SEM)] are parameters adjusted using a least-squares approach. The best nonlinear fit for the relation between fire incidence and total agriculture (red line) was $F = a[\exp(-b\sqrt{A_e})]A_e$, where A_e is the extensive agriculture fraction and a [404.62 ± 52.64 (SEM)] and b [2.96 ± 0.14 (SEM)] are parameters.

free methods of fallow management (*31*) and more diversified and sustainable agricultural and extractive practices (*32*) at a cooperative community level. This, however, would have consequences in further costs associated with machinery, training, and technical support to avoid leakage by emigration of farmers unable to comply with the financial demands of implementation and maintenance of fire-free management in their lands.

The success of reductions in carbon emissions by "avoiding deforestation" depends on harmonizing REDD with policies to limit fire incidence not only in the Brazilian Amazon but also in other rainforest nations in South America, Africa, and Asia. It brings to light the need for investments, in addition to the REDD finance mechanism, that aim to support "eco-friendly" land-use practices within local communities and Amazonian farmers and for monitoring systems that permit quantification of different types of forest degradation and secondary forest dynamics. Failure to tackle fire use in this region may discourage investors and donors within the REDD framework because of the risk that gains through deforestation reduction may be outweighed by carbon losses resulting from fire, as well as because of the lack of a comprehensive and reliable system for monitoring, reporting, and verifying emissions (MRV). Furthermore, fires in unmanaged forests as well as accidental fires that may not be classified as direct human-induced degradation are likely to go unreported if MRV processes mirror those on land use, land-use change, and forestry used by Annex I countries (*19*).

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Meiotic Recombination Provokes Functional Activation of the p53 Regulatory Network

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The evolutionary appearance of p53 protein probably preceded its role in tumor suppression, suggesting that there may be unappreciated functions for this protein. Using genetic reporters as proxies to follow in vivo activation of the p53 network in *Drosophila*, we discovered that the process of meiotic recombination instigates programmed activation of p53 in the germ line. Specifically, double-stranded breaks in DNA generated by the topoisomerase Spo11 provoked functional p53 activity, which was prolonged in cells defective for meiotic DNA repair. This intrinsic stimulus for the p53 regulatory network is highly conserved because Spo11-dependent activation of p53 also occurs in mice. Our findings establish a physiological role for p53 in meiosis and suggest that tumor-suppressive functions may have been co-opted from primordial activities linked to recombination.

The *p53* gene family mediates adaptive responses to genotoxic stress (*1*–*3*) and is broadly conserved (*4*, *5*). It is widely accepted that the p53 regulatory network is generally compromised in human cancers, but several lines of evidence indicate that during