APPLIED ECOLOGY

Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses

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Deforestation is the primary driver of carbon losses in tropical forests, but it does not operate alone. Forest fragmentation, a resulting feature of the deforestation process, promotes indirect carbon losses induced by edge effect. This process is not implicitly considered by policies for reducing carbon emissions in the tropics. Here, we used a remote sensing approach to estimate carbon losses driven by edge effect in Amazonia over the 2001 to 2015 period. We found that carbon losses associated with edge effect (947 Tg C) corresponded to one-third of losses from deforestation (2592 Tg C). Despite a notable negative trend of 7 Tg C year^{-1} in carbon losses from deforestation, the carbon losses from edge effect remained unchanged, with an average of 63 ± 8 Tg C year^{-1}. Carbon losses caused by edge effect is thus an additional unquantified flux that can counteract carbon emissions avoided by reducing deforestation, compromising the Paris Agreement's bold targets.

INTRODUCTION

Tropical forests play a crucial role in the global carbon cycle, with carbon stocks varying between 193 and 229 Pg (*1*, *2*), representing about 54% of the global aboveground carbon (AGC) stock (*3*). The area of these forests, however, declined by 10%, from 19.65 million km^2 in 1990 to 17.70 million km^2 in 2015, because of land-use and land-cover changes (*4*). The magnitude of these forest changes affects essential ecosystem services, including carbon storage, biodiversity, climate regulation, nutrient cycling, and water supply (*5*, *6*).

In Amazonia, the world's largest continuous tropical forest, deforestation has continuously converted old-growth forests into agricultural and livestock areas, fragmenting the landscape extensively. Forest fragmentation is associated with the increased number of forest patches and augmentation of the extent of forest edges perimeter and area (*7*, *8*). These changes in forest cover configuration cause direct carbon losses from edge effect and agricultural fire incursion into adjacent stand forests (*8*–*15*). The exposure of the Earth's forests to edge effect is widespread (*16*–*18*). Globally, about 70% of forests were within 1 km of forest edges in 2000 (*19*). However, only 5.2% of the forests in the Brazilian Amazon were in this same edge zone in 2014 (*7*).

Pioneering investigations from the BDFFP (Biological Dynamics of Forest Fragments Project), in the Brazilian Central Amazon, found significant carbon losses at forest edges (depth of 100 m) induced by microclimatic changes, leading to increased tree mortality rates.(*9*–*11*). However, the magnitude of carbon losses at these forest edges is still poorly quantified at large scales due to the scarcity of quantitative datasets for tropical forests. Efforts to accurately incorporate this source to regional and global carbon budgets are urgently needed for improving the estimations of the contribution of land-use and land-cover changes to the atmospheric carbon burden. This quantification is critical for the effectiveness of sustainable development policies and must be explicitly included either in national greenhouse gas inventories of tropical countries or in REDD+ (reducing emissions from deforestation and degradation) reports (*20*). Initial attempts were already made to quantify the carbon losses caused by edge effect in Amazonia (*21*–*27*); nonetheless, these studies were constrained by the availability of synoptic data, the accuracy of models, the spatial resolution of the remote sensing data used, or the study area extent.

Representing the environmental variability of edge effect and associated carbon stocks across Amazonia is a challenge due to its large area. In this context, remote sensing technologies play an essential role in quantifying both the extent of fragmentation-induced forest edges and the negative impact of edge effect on forest carbon stocks. The recent availability of 30-m spatial resolution forest change datasets (*28*) based on optical images from the Landsat series of Earth Observation satellites provides a unique opportunity to quantify forest edge extent and age in detail at pan-Amazonia scale. This information integrated with airborne LiDAR (light detection and ranging) technology collected over Amazonian forests offers a powerful combination for estimating forest carbon stocks in these areas, based on accurate models of forest structure (Fig. 1) (*29*, *30*).

Therefore, in this study, we aim to provide a unique spatially and temporally explicit quantification of carbon losses from forest edges and estimate the additional contribution to gross deforestation-induced carbon losses. Specifically, we (i) analyzed 16 years (2000–2015) of readily available 30-m spatial resolution Landsat-based forest cover and change datasets (*28*) to quantify the dynamics and age distribution

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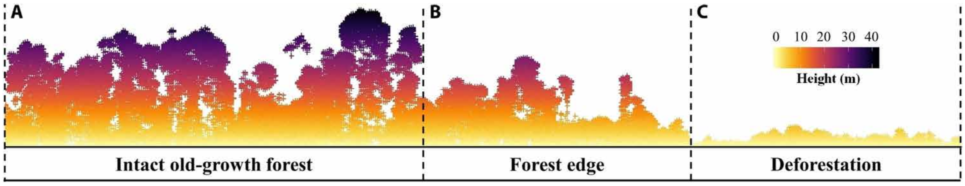

Fig. 1. LiDAR point cloud profile. Point cloud data collected in 2014 in the northeast of the Pará state, Brazil with 420 m of length. The points represent the vegetation height, which was normalized by the terrain altimetry. (**A**) Structure of a nondegraded old-growth forest, where the trees height reaches up to 40 m. (**B**) Forest edge (width of 120 m), where the height of the vegetation reaches up to 25 m. (**C**) Deforested area with vegetation regrowth (height up to 5 m).

of forest edges in Amazonia, (ii) processed an airborne LiDAR dataset collected across several locations in the studied area to build an empirical carbon loss model as a function of forest edge age, and last, (iii) modeled the edge-induced carbon loss across the entire Amazonia by applying the LiDAR-based carbon loss model across all pixels of the forest edge age maps. Our model is grounded on the observation (*31*) and concept (*32*) that tropical forest edges formed by deforestation continuously reduce their carbon stocks with age. Thus, we hypothesize that direct carbon losses by deforestation are followed by incremental indirect carbon losses induced by the aging of forest edges in Amazonia.

RESULTS

Forest edge dynamics and age distribution

The dynamics of forest edges creation and erosion (defined here as the complete removal of canopy cover of the forest edge) is explained directly by the pattern and pace of deforestation. In Fig. 2, we present our findings regarding Amazonian forest edges dynamics (Fig. 2, A and B) and their age distribution (Fig. 2, C and D). We estimate that 5% of the standing forest cover in 2000 was deforested between 2001 and 2015, or a gross forest loss of 273,195 km^2, at an average of 18,213 ± 4303 $km^2\ year^{-1}$ (Fig. 2A). We observed a deforestation peak of 26,376 km^2 in 2004 and a minimum value in 2013 (12,578 km^2). However, the Mann-Kendall test (MK) showed that annual deforestation overall decreased significantly at a rate of 683 $km^2\ year^{-1}$ (MK = −0.49 and $P < 0.05$) along the 15-year period.

During the interval studied, Brazil was the country with the highest deforestation rate (14,835 ± 4706 $km^2\ year^{-1}$), contributing with an average of 62 ± 10% $year^{-1}$ of overall deforestation in Amazonia (fig. S1). Brazil is also the leader in relative contribution rate (percentage of annual deforestation in relation to Amazonia area of each country), with an average of 0.355 ± 0.109% $year^{-1}$ (table S1). In contrast, French Guiana had the lowest deforestation rate (33 ± 18 $km^2\ year^{-1}$), contributing with an average of 0.20 ± 0.10% $year^{-1}$ of overall Amazonian deforestation, with a relative contribution rate average of 0.040 ± 0.021% $year^{-1}$ (table S1). However, across all Amazonian countries, only Brazil had a significant negative temporal trend in deforestation, at a rate of 773 $km^2\ year^{-1}$ (MK = −0.55 and $P < 0.05$), while Peru had the highest significant temporal trend of increase, at a rate of 68 $km^2\ year^{-1}$ (MK = 0.67 and $P < 0.05$). Details about annual deforestation rates and temporal trends for all countries in the Amazonia can be found in fig. S1 and tables S1 and S2.

In 2015, we estimated that forests edges, considering a depth of 120 m (*10*, *33*), covered an area of 176,555 km^2 across the whole Amazonia (Fig. 2A). This represents about 65% of the total deforested area between 2001 and 2015 or 3% of the total forest area in 2015 over the region. On average, 11,770 ± 3546 $km^2\ year^{-1}$ of new forest edges were created in Amazonia, with a maximum area of 17,815 km^2 in 2012 and a minimum of 6481 km^2 in 2011 (Fig. 2A). Brazil and Peru had the highest annual edge creation average, contributing with 7600 ± 3427 $km^2\ year^{-1}$ and 1510 ± 300 $km^2\ year^{-1}$, respectively. In addition, we quantified that on average, 7 ± 1, 24 ± 4, and 42 ± 3% of the forest edges were eroded by forest-clearing process after 1, 5, and 10 to 14 years of their creation, respectively (Fig. 2B).

Similar to the patterns found for deforestation rates in the Amazonia, the creation of forest edges decreased significantly at a rate of 707 $km^2\ year^{-1}$ (MK = 0.74 and $P < 0.05$) between 2001 and 2015 (Fig. 2A). Across all Amazonian countries (table S1), Brazil and Colombia had a significant decreased trend in edge formation ($P < 0.05$), with rates of 683 and 49 $km^2\ year^{-1}$, respectively. Conversely, Guyana and Suriname had a significant increased trend ($P < 0.05$), with rates of 5 and 11 $km^2\ year^{-1}$, respectively. Details about temporal trends of forest edge dynamics for Amazonian countries are shown in fig. S2 and table S3.

In 2015, we observed that the oldest edges (between 10 and 15 years old) were distributed mainly over the Brazilian Arc of Deforestation (*34*), an old Amazonian deforestation frontier located in the southeast flank of Amazonia (Fig. 2C). We also observed old forest edges in the southern portion of Bolivia and in the north of Amazonia, including three countries: Colombia, Venezuela, and Guyana. On the other hand, the youngest forest edges (between 1 and 3 years old) dominated not only the new active deforestation frontiers in southern Bolivia, western Peru, and northern Colombia but also areas in the central Brazilian Amazon.

On average, forest edges in Amazonia were 7 ± 3 years old in 2015. The edge age distribution was close to uniform: 23% of the forest edges ages were between 1 and 3 years, 21% between 4 and 6 years, 19% between 7 and 9 years, 20% between 10 and 12 years, and 16% between 13 and 15 years. Considering all Amazonian countries, the age of forest edges spanned from an average of 6 ± 3 years in Suriname to 8 ± 3 years in Colombia (Fig. 2D and Table 1). The Kruskal-Wallis test (KW) showed a significant difference (KW = 1179 and $P < 0.05$) in the age of forest edges among the Amazonian countries (Fig. 2D). For instance, we found that forest edge age was significantly ($P < 0.05$) lower in Suriname (group e) and higher in Colombia (group a). However, the age of forest edges in the pair Brazil and Venezuela (group b) and in the group Ecuador, Guyana, and Peru (group d) was statistically indistinguishable from each other. Last, the age of forest edges in French Guiana (cd group) was not distinguishable from countries belonging to groups c and d, simultaneously.

Spatial-temporal variation in AGC losses

By combining the age information from the mapped forest edges with the airborne LiDAR data, we established a relationship depicting

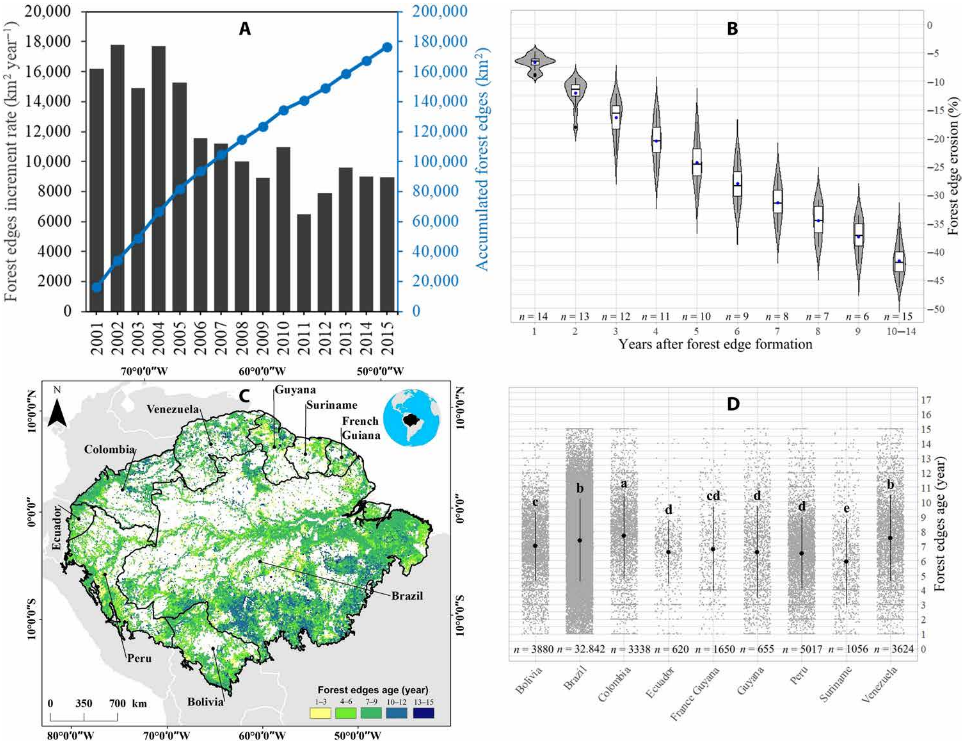

Fig. 2. Forest edges creation, erosion, and age composition in Amazonia. (**A**) Temporal forest edges variation in Amazonia, where the black bars are the annual forest edges increment rate and the blue line is the total gross forest area increment from 2001. (**B**) Boxplots of forest edges erosion rates (as a negative percentage) for Amazonia, where the bold horizontal lines are the medians, the blue dots are the averages, the shaded area is the frequency distribution function, and *n* is the number of observations. (**C**) Spatial distribution of forest edges age in 2015 in Amazonia; ages were aggregated by the average in a 10 km by 10 km grid cell to improve visualization. (**D**) Dot plots of forest edge age [each dot corresponds to a single grid cell in (C)] in Amazonian countries in 2015, where the vertical bars are the SDs, the black dots are the averages, the gray dots are the data observations, and *n* is the number of observations. The letters in bold represent the groups defined by the post hoc test.

Table 1. Average and median of the forest edges ages for the Amazonian countries.

Country	Forest edges ages (years)	
	Average ± SD	**Median**
Bolivia	7.00 ± 2.35	7.01
Brazil	7.38 ± 2.84	7.54
Colombia	7.67 ± 2.88	7.96
Ecuador	6.58 ± 2.17	6.84
France Guyana	6.57 ± 3.11	6.41
Guyana	6.78 ± 2.91	6.57
Peru	6.48 ± 2.50	6.56
Suriname	5.94 ± 2.93	5.49
Venezuela	7.53 ± 2.94	7.59

the loss of aboveground forest carbon as a function of the age of forest edges (see Materials and Methods) to investigate the spatial and temporal changes of carbon stocks associated with edge effect across Amazonia. As shown in Fig. 3 (A and B) between 2001 and 2015, carbon losses related to edge effect ranged from 0.001 up to 0.252 Tg C per grid cell (100 km^2), while losses from deforestation ranged from 0.001 up to 0.799 Tg C per grid cell. More than 60% of the grid cells had values of carbon loss varying between 0.001 and 0.022 Tg C, both for edge effect and deforestation (Fig. 3, C and D). Spatially, absolute carbon loss values associated with edge effect and deforestation presented similar patterns across Amazonia (Fig. 3, A and B), with substantial accumulated losses over the Brazilian Arc of Deforestation (*34*) and the southwest Amazonian flank. The lower accumulated losses were spatially distributed over the central and the northern part of Amazonia.

Figure 3E shows the relative contribution of edge effect and deforestation for the total carbon loss between 2001 and 2015 as a percentage of each grid cell. We found that relative contribution of edge effect and deforestation for the carbon loss of grid cells were heterogeneous across Amazonia during the studied period. While carbon losses from edge effect dominated mainly the central Amazonia region, carbon loss associated with deforestation were more evident along the Brazilian Arc of Deforestation (*34*) and areas in Peru, Bolivia, and southern French Guiana.

Between 2001 and 2015, we estimated a total gross carbon loss from edge effect of 947 Tg C (0.95 Pg C), with an average of 63 ± 8 Tg C year^{-1} between 2001 and 2015 in Amazonia. We did not identify any temporal trend in the time series (Sen's slope = −0.22 Tg C year^{-1}, MK = −0.01, and $P > 0.05$). We observed a carbon loss peak of 78 Tg C in 2005, while we recorded a minimum loss of 41 Tg C related to edge effect in 2001 (Fig. 4A). In contrast, the total gross carbon loss from deforestation was 2592 Tg C (2.59 Pg C), with an average of 173 ± 46 Tg C year^{-1}, and a significant negative temporal trend of

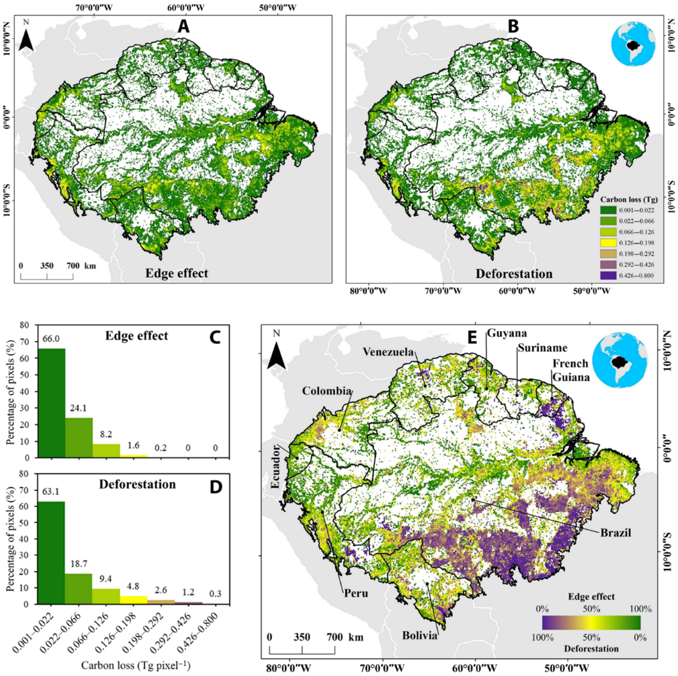

Fig. 3. Spatial variability of carbon losses in Amazonia. Spatial variability of carbon losses between 2001 and 2015 from (**A**) edge effect and (**B**) deforestation. Histograms of frequency distribution of carbon losses related to (**C**) the edge effect presented in (A) and (D) the deforestation presented in (B). (**E**) Percent contribution of edge effect and deforestation to the total carbon loss of each pixel in Amazonia. Carbon losses were aggregated by the sum in a 10 km by 10 km grid cell to improve visualization in (A) and (B).

6.90 Tg C year^{-1} (MK = –0.51 and $P < 0.05$) between 2001 and 2015. Unlike the observed pattern of carbon loss from forest edges, the peak of deforestation-related carbon loss occurred in 2004 (261 Tg C), and the minimum was recorded in 2013 (114 Tg C) (Fig. 4B). Across all Amazonian countries, Brazil had the most substantial contribution for the Amazonia-wide carbon loss from both forest edges and deforestation, representing an average of 67 ± 6% year^{-1} and 79 ± 7% year^{-1}, respectively (Fig. 4, A and B). At the same time, Suriname's forest edges and deforestation had the lowest contribution, with an average of 1.03 ± 0.57% year^{-1} and 0.48 ± 0.35% year^{-1}, respectively (Fig. 4, A and B).

Overall, our findings show that the deforestation process leads to a collateral carbon loss of 37% related to the dynamics of forest edges in the Amazonia. Most notably, unlike the carbon loss from deforestation, which declined significantly during the analyzed period, the additional carbon loss associated with the edge effect remained unchanged over time. Note that the difference between carbon losses from deforestation and edge effect decreased over time. In 2001, deforestation promoted a loss of 122 Tg C greater than that observed for the edges; however, in 2015, this difference decreased to 66 Tg C (fig. S3A). During the studied period, hence, the carbon loss from forest edges that contributed to 25% of the loss from deforestation in 2001 increased to 48% in 2015 (fig. S3B). In 2013, carbon loss induced by edge effect was more than half (54%) of the direct deforestation loss (fig. S3B).

The analysis of temporal trend and average of carbon losses associated with edge effect and deforestation across all Amazonian countries (Table 2) showed that Ecuador, Guyana, Peru, and Suriname had a significant ($P < 0.05$) positive trend in carbon losses, both by edge effect and deforestation, varying between 0.01 and 0.41 Tg C year^{-1} for edge effect and between 0.01 and 0.65 Tg C year^{-1} for deforestation. Only Brazil had a significant ($P < 0.05$) negative temporal trend of deforestation-associated carbon loss, although loss from edges remained unchanged ($P > 0.05$) over time. In contrast, Venezuela had a significant ($P < 0.05$) positive trend in carbon loss from deforestation, but losses from edge effect remained unchanged ($P > 0.05$) over time.

DISCUSSION

Trends in deforestation across Amazonian countries

From our approach, we observed a significant decline in forest clearing processes between 2001 and 2015 in Amazonia. This decline followed the reduction in the deforestation rates observed in Brazil. The reduction in deforestation rates observed here for the Brazilian portion of Amazonia corroborates the progressive decline reported by the official deforestation system operating in Brazil (fig. S1) (*35*). This reduction was a result of the strengthening of policies for prevention and control of deforestation in the region called Brazilian Legal Amazon, consolidated since the creation of the PPCDAm (Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal; Action Plan for Prevention and Control of Deforestation in the Legal Amazon) in 2004 (*36*). During the first three phases of the PPCDAm (2004–2015), policies were created and actions implemented, including the creation and consolidation of near–real time systems for monitoring deforestation based on remote sensing, the intensification of law enforcement, the restriction of credit for illegal loggers, the creation and consolidation of conservation units and indigenous lands, and advances in land policy, such as the Rural Environmental Registry (Cadastro Ambiental Rural) (*37*). However, from 2013 to 2019, an upward trend was observed in the official deforestation rates (*35*), marked by an impressive rate of 10,129 km^2 in 2019, an increase of 34% compared to 2018 (7536 km^2), the highest rate since 2008 (12,911 km^2). This upward trend was induced by environmental setbacks such as controversial changes in the Brazilian Forest Code in 2012 (*38*), the recent weakening of deforestation enforcement, the dismantling of climate change policies (including the interruption of the PPCDAm from 2019), and the possibility of regularization of public lands illegally grabbed (Bill n° 2633/2020, former Provisional Measure n° 910/2019) (*39*, *40*).

Although the PPCDAm was a key step for the reduction of the deforestation in the Brazilian Amazon, other external factors such as the soy and beef moratoria (*41*) also played a critical role. Companies associated with the agribusiness agreed upon an embargo on soy and beef produced in illegal deforested areas. All these policies and actions inhibited illegal deforestation activities in the Brazilian Amazon, resulting in the significant decline of deforestation rates in Brazil after 2004. This pattern drove the overall trend of deforestation reduction across Amazonia.

Countries such as Ecuador, Guyana, Peru, and Suriname had, however, a significant increase in deforestation rates between 2001 and 2015. In Ecuador, the deforested areas were associated with increased commodity prices between 2005 and 2014, intensifying mineral and hydrocarbon extraction, agriculture production, logging, and palm cultivation (*42*, *43*). In Guyana (*43*, *44*), Suriname (*43*, *45*), and Peru (*43*, *46*), on the other hand, the increase in

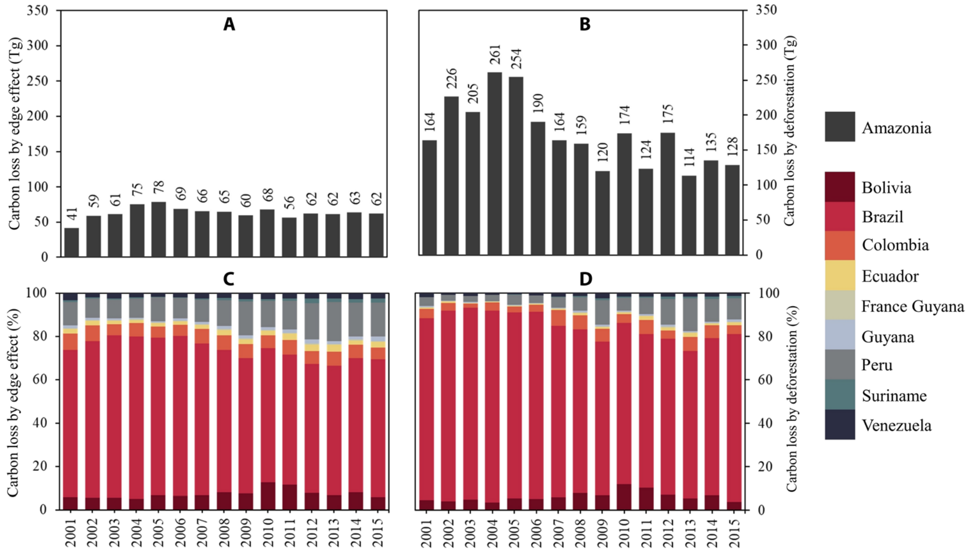

Fig. 4. Temporal variability of carbon losses in Amazonia. (**A**) Temporal carbon loss variability by fragmentation. (**B**) Temporal carbon loss variability by deforestation. The bottom panels show the contribution as a percentage of each country to the annual carbon loss by edge effect (**C**) and deforestation (**D**).

Table 2. Temporal trend and average carbon losses induced by edge effect and deforestation for all Amazonian countries. Where S is the Man-Kendell statistics. The S statistic with an asterisk (*) means a significant temporal trend at 95% of significance level ($P \leq 0.05$).

Country	Edge effect			Deforestation		
	S	Sen's slope (Tg C year^{-1})	Average ± SD (Tg C year^{-1})	S	Sen's slope (Tg C year^{-1})	Average ± SD (Tg C year^{-1})
Bolivia	0.37	0.14	5 ± 1.41	−0.03	−0.02	10 ± 3.60
Brazil	−0.31	−0.58	42 ± 7.67	−0.61*	−8.41	139 ± 47.68
Colombia	−0.11	−0.03	4 ± 0.47	−0.15	−0.02	8 ± 1.97
Ecuador	0.71*	0.06	1 ± 0.34	0.51*	0.08	1 ± 0.53
France Guiana	0.35	0.01	0 ± 0.06	0.15	0.01	0 ± 0.20
Guyana	0.71*	0.04	1 ± 0.23	0.41*	0.04	1 ± 0.28
Peru	0.73*	0.41	8 ± 1.97	0.63*	0.65	11 ± 4.25
Suriname	0.83*	0.07	1 ± 0.36	0.75*	0.07	1 ± 0.49
Venezuela	0.45*	0.02	1 ± 0.17	0.09	0.01	2 ± 0.52

deforestation rates was mainly induced by activities related to illegal gold mining at different scales. Last, countries such as Bolivia, Colombia, French Guiana, and Venezuela had constant deforestation rates (no significant trends) between 2001 and 2015. These deforested areas were the result of agricultural, livestock, and mining activities (*43*, *44*, *47*, *48*), which potentiate the collateral impacts of edge effect on forest degradation and biodiversity loss (*49*).

The collapse of AGC stocks in forest edges

Consistent with the decline in deforestation, we identified a significant decrease in the annual forest edge formation in Amazonia. The dynamics of forest edge formation result from the spatial and temporal patterns of deforestation, which defines the spatial arrangements and the geometries of the forest fragments (*50*, *51*). Landscapes arising from the deforestation process associated with the establishment of rural settlements (fish bone pattern) have up to five times more forest edge areas per deforested land than landscapes dominated by large (regular shape) farms (*51*). The average rate of erosion of 11.47% within 3 years after forest edges creation and its subsequent increase to 42.80% after 12 years, found in our study, are lower than those found in previous studies at the local scale in Amazonia (*22*, *50*). The lower rates found here are likely to be a result of two nonexclusive processes, including a significant decrease in deforestation rates and the creation of more regular shape deforested polygons.

The drivers and historical trends of deforestation and forest edge creation are country specific (*50*). Bolivia, Colombia, Venezuela, Peru, and Suriname presented a large proportion of forest edges areas with 1 to 6 years old, which is explained by the intensification of deforestation in these countries in recent years (*52*). The other Amazonian countries, as Brazil, have older forest edges areas, due to an older and more consolidate deforestation frontier, which stabilized by the end of the study period (*52*).

Our findings indicated that aboveground forest carbon progressively decreased in Amazonian forest edges as a function of their ages (fig. S13). This pattern is corroborated by similar results found in Sabah, Malaysian Borneo (*31*). The losses observed in our study are greater in the first 5 years after the edge creation, which are consistent with field observations in controlled experiments in the Brazilian Central Amazon (fig. S4A) (*10*, *27*). Following forest edge formation, mortality rates increase significantly (fig. S5C), in particular among larger trees, which store most of the forest's carbon (*53*, *54*). In addition, microclimatic changes tend to increase wind turbulence and fire promoting an exacerbation of disturbance rates in the forest edges (*55*–*59*). Together, these effects cause a steep initial reduction in carbon stocks following the edge formation. Subsequently, with the aging of the edges, turnover rates (*60*), number of woody lianas (*10*), and pioneer species increase, as a result of the successional process (*33*). Following this process, the plant community established in the forest edge tends to be better adapted to the new microclimatic conditions, sealing the edges (fig. S5D) and reducing the susceptibility to further microclimatic changes (*56*, *61*–*63*). Although growth of new trees increases over time, turnover rates also increase (*64*), as a consequence of increasing mortality, so our age-carbon loss function (fig. S13) capture the tendency of forest edges to reach an alternative postfragmentation equilibrium state. This alternative state, which stabilizes between 6 and 15 years after the edge creation, is characterized by forests with lower aboveground biomass (AGB) than adjacent core areas. Field observations in controlled experiments in the Central Brazilian Amazon demonstrated a significant reduction in canopy height, basal area, and AGB of up to 10 years after edge formation (*27*). The relationship between distance to edge and AGB was, however, no longer significant after 22 years of edge formation (*27*). Differently from Almeida *et al.* (*27*), in our analyses, the AGB values are likely to remain below prefragmentation levels after 15 years, because most of the Amazonian forest edges are constantly exposed to the incidence of fire, which in the Brazilian Amazon can lead to a reduction in forest AGB of 24.8 ± 6.9% after 31 years (fig. S6) (*64*). We expect the recovery of Amazonian forest edges in few areas where secondary forests are growing adjacent to these edges; however, these areas are likely to be minor as secondary forests in the Brazilian Amazon are limited to 34% (in 2018) of the total deforested area (1988–2018 period) (*35*, *65*).

The estimated AGC losses in our study are considerably higher (24.93 ± 4.53% of difference) than those found by Laurance *et al.* (*10*) in the local scale BDFFP long-term experiment (fig. S4B). These differences are expected as our Amazonia-wide analysis captures variations in factors influencing the stability of AGC in forest edges not contemplated by controlled local-scale experiments such as: (i) multiple configurations of size, shape and types of land use, and land cover surrounding the forest edges (*66*) and mainly, (ii) the impact of fires on forest edges (*54*, *64*). In Amazonia, fire typically occurs in forest edges (*8*, *13*, *15*, *67*–*69*) by escaping from deforested areas, pastures, and agricultural fields and leaking into surrounding forests (*70*, *71*). Moreover, fire in forest edges often damages the remaining trees, increasing their vulnerability to strong wind events, enhancing tree mortality rates (*72*). Last, during the 21st century, Amazonia has been exposed to an increased frequency of extreme droughts (*73*, *74*), which may induce the reduction in forest carbon stocks, either by the direct effect of drought on tree mortality (*75*) or by the collateral effect of increased fire incidence at the forest edges during these extreme events (*76*–*78*).

Implications for carbon emissions reduction policies

Here, we showed at Amazonian scale that forest carbon loss induced by edge effect was one-third of the carbon loss caused by deforestation during the 2001 to 2015 period. Furthermore, our trend analysis showed that although deforestation-related carbon loss decreased significantly between 2001 and 2015, edge effect–related carbon loss remained unchanged. Knowing that part of the carbon losses in the forest edges is emitted to the atmosphere following the decomposition process, our findings show that deforestation-induced edge effect can indirectly increase emissions from deforestation alone by 37%, with implications for policies aiming to reduce in carbon emissions by avoiding deforestation.

To show the impact of neglecting carbon losses from edge effect on the calculation of gross deforestation emissions (fig. S7), we compared (Wilcoxon's test) carbon losses from each process before (between 2001 and 2004) and after (between 2005 and 2015) the implementation of the PPCDAm (*36*). The PPCDAm was the central policy responsible for the decline in deforestation rates in the Brazilian Amazon (*35*, *36*). We found that annual carbon loss associated with deforestation alone decreases significantly (41%; $W = 40$ and $P = 0.02$) from 187 ± 21 Tg year^{-1} in the pre-PPCDAm period to 111 ± 39 Tg year^{-1} in the post-PPCDAm period. The annual carbon loss associated with edge effect, conversely, in the pre-PPCDAm phase (43 ± 6 Tg year^{-1}) was not statistically different ($W = 25$ and $P = 0.75$) from the value calculated for the post-PPCDAm period (40 ± 7 Tg year^{-1}).

Our analysis points to two critical issues: first, because the carbon loss induced by edge effect is persistent over time, even with deforestation slowing down, extra emissions from the newly formed edges reduce the effectiveness of actions for reducing carbon emissions by avoiding deforestation, such as the REDD+ policy. The inclusion of the edge effect process into systems for monitoring, reporting, and verifying emissions is, hence, crucial. Second, we show that reducing deforestation carbon loss does not change edge-induced carbon loss, indicating the need of new mechanisms to avoid or to compensate the potential carbon emissions associated with edge effect. These could be related to landscape planning, which is necessary to be implemented not only in Amazonian countries but also in other tropical countries such as Africa and Asia. Besides, the recent deforestation upward trend in the Brazilian Amazon has a negative implication, the increase in carbon losses from deforestation, directly, and edge effect induced by the creation of new forest edges.

Decreasing uncertainties in emissions estimates from land-use and land-cover change can support the establishment of more effective national actions, helping Amazonian countries to accomplish with emission reductions targets proposed at international climate agreements, such as the Paris Agreement. The Paris Agreement aims to establish volunteer emission reduction actions and targets by the signatory countries to be reached by 2025, to strengthen the global response to the threat of climate change (*79*). For combating the effects of climate change, it is critical to maintain the global average temperature rise below 2°C from preindustrial levels and efforts to limit the temperature increase to 1.5°C (*80*). To achieve this goal, there is a pressing need for a 45 and 100% reduction in greenhouse gas emissions by 2030 and 2055, respectively (*81*). Our results indicate that there is a significant missing source to be considered in the Amazonian carbon budget. Including carbon losses related to edge effect in regional and global carbon budgets is, hence, crucial for accurately estimate the land-use and land-cover change contribution to the atmospheric carbon burden. In conclusion, carbon losses associated with the edge effect in Amazonia are an additional unquantified carbon flux that can counteract carbon emissions avoided by reducing deforestation, compromising the Paris Agreement's bold targets.

MATERIALS AND METHODS

Our materials and methods are included in the following five steps: (i) forest cover mapping, (ii) identification of forest edges and quantification of age structure, (iii) carbon stock mapping from LiDAR data, (iv) carbon stock loss model by edge effect and deforestation, (v) statistical analysis, and (vi) sources of uncertainty. Detailed information about each of these steps is provided in the Supplementary Materials.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/40/eaaz8360/DC1

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