EMISSIONS FROM FOREST DEGRADATION COUNTERACTED MORE THAN HALF OF THE BRAZILIAN AMAZON DEFORESTATION REDD+ RESULTS

Celso H. L. Silva-Junior[1], Luiz E. O. C. Aragão[2], Liana O. Anderson[3], Nathália S. Carvalho[2], Ana C. M. Pessôa[3], João B. C. Reis[3], Ricardo Dalagnol[1], Fabien H. Wagner[1], and Sassan S. Saatchi[1]

[1]University of California, Los Angeles, USA, {celsohlsj, dalagnol, fhwagner}@ucla.edu, sasan.s.saatchi@jpl.nasa.gov;
[2]Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, luiz.aragao@inpe.br, nathalia.bioufla@gmail.com;
[3]Centro de Monitoramento de Alertas de Desastres Naturais, São José dos Campos, SP, Brasil,
liana.anderson@cemaden.gov.br, acmoreirapessoa@gmail.com, joaodosreis89@gmail.com

ABSTRACT

Tropical forests provide essential ecosystem services, including carbon storage, biodiversity, and climate regulation. However, deforestation and forest degradation compromise the ability of forests to provide ecosystem services, including the loss of carbon stocks that go into the atmosphere. Here we test the hypothesis that the edge effect and forest fire emissions can counteract the Brazilian Amazon deforestation REDD+ results. For this, we used a remote sensing dataset including old- and secondary-growth forests, burned areas, and aboveground carbon stocks. We found that emissions from edge effects and forest fire (5038 Tg CO_2eq) counteracted 68% of the Brazilian Amazon REDD+ results (7413 Tg CO_2eq); secondary forests' uptake during this period (244 Tg CO_2eq) was insufficient to compensate for the annual emissions from degradation.

***Keywords* —** forest fires, climate change, forest fragmentation, COP27, greenhouse gases.

1. INTRODUCTION

Tropical forests provide essential ecosystem services, including carbon storage, biodiversity, and climate regulation [1]–[3]. However, deforestation decreased these forests by 10% from 1990 to 2015 [4]. In the Amazon, deforestation leads to large-scale forest fragmentation that increases the extent of forest edges [5], [6]. In addition, forest edges impacted by changes in the forest microclimate, such as humidity, temperature, and wind, cause loss of carbon stocks by increasing tree mortality and spreading fires.

During the 2006-2019 period, Brazil reported an emission reduction from deforestation of 7413 Tg CO_2eq (530±167 Tg CO_2eq y^{-1}) to the United Nations Framework Convention on Climate Change - UNFCCC under the Reducing Emissions from Deforestation and Forest Degradation - REDD+ program [7]. However, this estimate does not include emissions from forest degradation (e.g., forest edges and fires). Here, we hypothesized that the edge effect and fire committed emissions can counteract the carbon credits developed from avoided deforestation [8], [9].

To test our hypothesis, we calculate the net emissions by estimating carbon loss from forest degradation (edge effects and forest fires) and gain from secondary forests using a remote sensing approach. All the estimates were performed for the entire Brazilian Amazon biome.

2. MATERIAL AND METHODS

4.1. Datasets

To test the hypotheses, we used a remote sensing dataset that included:

Old- and secondary-growth forests - we used the unprecedented nearly 40-year mapping at a 30-m spatial resolution of Tropical Moist Forests (TMF). From a time series of images from the Landsat satellites collected between 1982 and 2020, Vancutsem et al. (2021) [10] mapped deforestation, forest degradation, and forest regrowth. In the TMF dataset, forest degradation events are changes at a forest pixel visible for less than 2.5-years. In contrast, deforestation (the total forest cover removal) are disturbances that last longer than 2.5-years. On the other hand, secondary forests were defined as pixels with forest regrowth after no forest cover for more than 2.5-years.

Burned area - we used three burned area products to ensure the highest number of forest fires in our analyses. The first product was MapBiomas Fire [11], with a 30-m spatial resolution; the second was the MCD64A1 product [12], with a 500-m spatial resolution; and finally, the FIRE-CCI product [13], with a 250-m spatial resolution. The three products were combined in annual maps of burned areas. Only the regions burned that overlap forest cover (forest fires) were kept for the analyses.

Aboveground carbon stocks - we adopted the potential aboveground carbon map from Brazil's Forest Reference Emission Level for Amazon (FREL-C; http://ftp.cptec.inpe.br/pesquisa/p4cn/3%20Inventario- NC) [14] to maintain methodological consistency with official data. Each map pixel of the 30-m spatial resolution represents the density of carbon given in Mg C ha^{-1}.

4.1. Degradation CO_2 emission model

Here we use a simple model to estimate carbon emissions due to forest degradation (edge effect and forest fires). We considered the period from 2001 to 2019; although we only used emissions in the period 2016-2019 when we have the REDD+ deforestation results. In our model, we assume as initial carbon stocks the carbon density in each pixel of the FREL-C map.

To avoid double counting emissions due to overlap between disturbances we only considered wildfires without overlapping forest edges. In addition, at each time step from the year 2002 onwards, the carbon map was updated to reflect the carbon losses in each year analyzed.

The calculations of carbon emissions from forest fire and edge effect were calculated according to Equations 1 and 2, respectively. The method for forest fire emission was adopt from Campanharo et al. (2019) [15] and for edge effect emissions from Silva-Junior et al. (2020) [9]. For forest fire we consider the 2001-2019 time window, and for edges effects the 1991-2019 time window.

$$E_{forest\ fires} = AGC * 0.09 * 0.292 * 3.667 \quad (1)$$

$$E_{edge\ effects} = \frac{AGC * 0.09 * 0.358 * 3.667}{(Age + 0.836) * (Age - 0.164)} \quad (2)$$

were, $E_{forest\ fire}$ and $E_{edge\ effect}$ are the amount of CO_2eq emission for each pixel give in Mg ha^{-1}; *AGC* is the potential aboveground carbon stock; *Age* is forest edge age for a given pixel; 0.09 is the factor for converting carbon density into total carbon for each 30-m pixel; 0.292 is the fraction of carbon loss due to fire [16]; and 3.667 is the factor for converting carbon into carbon dioxide equivalent (CO_2eq). The other terms of the equations are constants.

We adopted the relative recovery curve (%) of aboveground biomass in tropical secondary forests proposed by Poorter et al. (2021) [17] to estimate the uptake potential in the tropical region between 1991 e 2019.

Through the secondary growth forests cover from Vancutsem et al. (2021) dataset, we calculate year by year the age of these forests when remaining in the year under analysis. Then, through the potential AGC map, we apply Equation 9 in a pixel approach.

$$Uptake_{Pixel} = AGC_{Pixel} \cdot f \cdot 3.667 \quad (3)$$

were, $Uptake_{Pixel}$ is the amount of uptake CO_2 (in Tg) for a given year, AGC_{Pixel} is a pixel in the potential AGC map, f is an uptake factor for a given secondary forest age [17], and 3.667 is a factor to convert carbon in CO_2.

3. RESULTS AND DISCUSSION

Between 2006 and 2019, Brazil reported a total deforestation emission for the Amazon biome of 5697 Tg CO_2eq (or 407±136 Tg CO_2eq y^{-1}) (Figure 1) [7], with a clear increasing trend from 2012. On the other hand, our results show that emissions from forest edges and fires (degradation) reached 5038 Tg CO_2eq (or 360±92 Tg CO_2eq y^{-1}), during the same period (Figure 1). Thus, emissions from forest degradation, on average, represented 96±35% of emissions from deforestation, with 48% in 2008 and 187% in 2015.

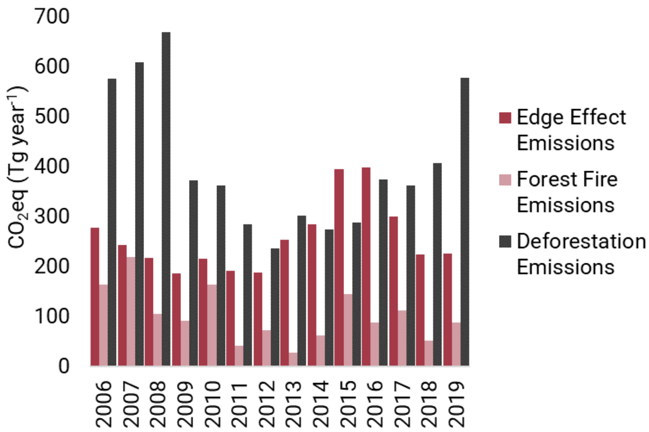

Figure 1. Annual carbon dioxide (CO_2) emissions from deforestation [7], forest fires, and edge effect within the Brazilian Amazon.

In addition, emissions from forest degradation were equivalent to 68% of the Brazilian Amazon REDD+ results (7413 Tg CO_2eq) (Figure 2a). Furthermore, secondary forests' uptake during this period (17±11 Tg CO_2eq y^{-1}; total of 244 Tg CO_2eq) was insufficient to compensate for the annual emissions from edge effects (7±5% y^{-1}) and forest fire (24±20% y^{-1}). We highlight that 2016 and 2019 alone, emissions from forest degradation compromised the full REDD+ results, even with secondary forest uptake (Figure 2b). Thus, we confirmed the hypothesized that the edge effect and forest fire emissions can counteract the carbon credits developed from avoided deforestation.

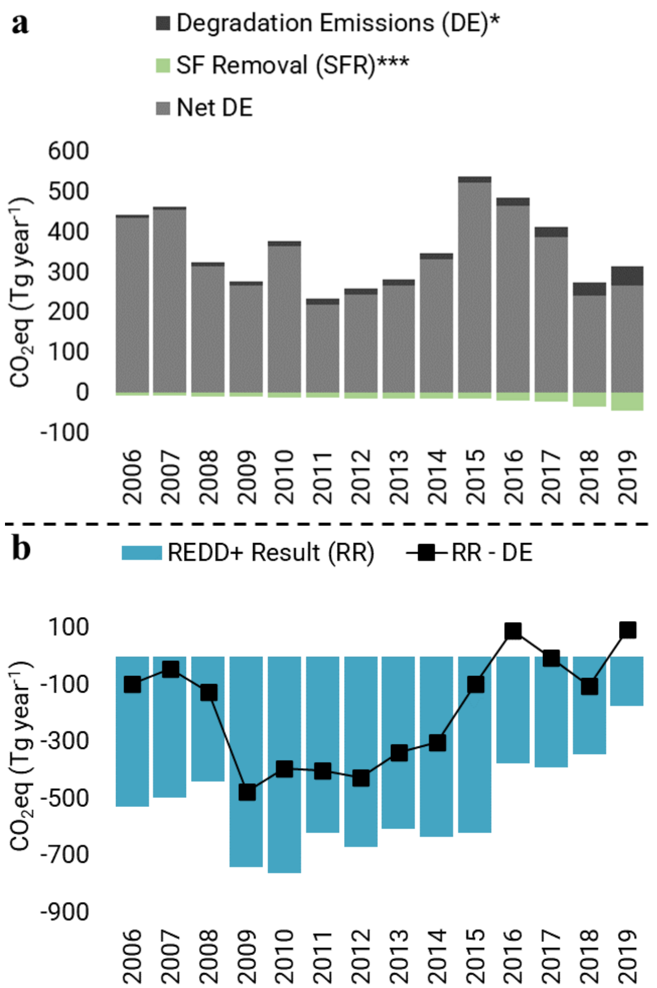

Figure 2. (a) Balance of carbon dioxide (CO_2) emissions and removals from forest fires, edge effect, and secondary forests in the Brazilian Amazon. (b) The balance between the Brazilian Amazon deforestation REDD+ results and CO_2 emissions from forest degradation (forest fires and edge effect).

The deforestation emissions increase observed from 2012 onwards, which resulted in a reduction in Brazil's results, is mainly due to the deforestation rate increase in the Brazilian Amazon, caused by changes in the Brazilian Forest Code in 2012 and the recent environmental setbacks in Brazil [18].

In addition to the urgency to stop the escalation of deforestation in the Brazilian Amazon, we showed that edge effects and forest fires could compromise a national REDD strategy focused exclusively on reducing emissions from deforestation. Thus, when necessary, legal deforestation must be done based on territorial planning to create a minimum amount of forest edges. Furthermore, a fire management policy in the region is urgent to avoid uncontrolled fires [19], especially during years of extreme drought [20]–[22].

5. CONCLUSIONS

Here we showed that forest degradation can compromise a national REDD+ strategy focused exclusively on reducing emissions from deforestation. Brazilian decision-makers, therefore, should take urgent action to stop the climb of deforestation and develop a fire-free policy and fire use substitution program for Amazon. Furthermore, in our analysis, emissions from selective cutting, another important source of emissions, were not included; this source will be included in future works.

Finally, we recommend that emissions from edge effects and secondary forest removals to be quantified and reported together with emissions from deforestation and forest fire as a degradation source, thus allowing better quantification of the atmosphere's greenhouse gas fluxes.

8. REFERENCES

[1] P. Artaxo *et al.* Tropical forests are crucial in regulating the climate on Earth, *PLOS Climate*, v. 1, p. e0000054, Aug. 2022.

[2] E. G. Brockerhoff *et al.* Forest biodiversity, ecosystem functioning and the provision of ecosystem services, *Biodiversity and Conservation*, v. 26, pp. 3005–3035, Dec. 2017.

[3] S. Díaz, A. Hector, and D. A. Wardle. Biodiversity in forest carbon sequestration initiatives: not just a side benefit, *Current Opinion in Environmental Sustainability*, v. 1, pp. 55–60, Oct. 2009.

[4] R. J. Keenan *et al.* Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015, *Forest Ecology and Management*, v. 352, pp. 9–20, Sep. 2015.

[5] L. B. Vedovato *et al.* The extent of 2014 forest fragmentation in the Brazilian Amazon, *Regional Environmental Change*, v. 16, pp. 2485–2490, Dec. 2016.

[6] C. H. L. Silva-Junior *et al.* Forest Fragmentation and Fires in the Eastern Brazilian Amazon–Maranhão State, Brazil, *Fire*, v. 5, p. 77, Jun. 2022.

[7] Brasil. Technical Annex I: results achieved by Brazil from reducing emissions from deforestation in the Amazon biome for REDD+ results-based payments, in *Fourth National Communication of Brazil to the UNFCCC*, 2020.

[8] L. E. O. C. Aragao *et al.* The Incidence of Fire in Amazonian Forests with Implications for REDD, *Science*, v. 328, pp. 1275–1278, Jun. 2010.

[9] C. H. L. Silva-Junior *et al.* Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses, *Science Advances*, v. 6, p. eaaz8360, Oct. 2020.

[10] C. Vancutsem *et al.* Long-term (1990–2019) monitoring of forest cover changes in the humid tropics, *Science Advances*, v.

7, p. eabe1603, Mar. 2021.

[11] A. A. C. Alencar *et al.* Long-Term Landsat-Based Monthly Burned Area Dataset for the Brazilian Biomes Using Deep Learning, *Remote Sensing*, v. 14, p. 2510, May 2022.

[12] L. Giglio *et al.* The Collection 6 MODIS burned area mapping algorithm and product, *Remote Sensing of Environment*, v. 217, pp. 72–85, Nov. 2018.

[13] E. Chuvieco *et al.* Generation and analysis of a new global burned area product based on MODIS 250 m reflectance bands and thermal anomalies, *Earth System Science Data Discussions*, pp. 1–24, May 2018.

[14] Brasil. *Brazil's submission of a Forest Reference Emission Level (FREL) for reducing emissions from deforestation in the Amazonia biome for REDD+ results-based payments under the UNFCCC from 2016 to 2020*. MMA, Brasília, 2018.

[15] W. Campanharo *et al.* Translating Fire Impacts in Southwestern Amazonia into Economic Costs, *Remote Sensing*, v. 11, p. 764, Mar. 2019.

[16] L. O. Anderson *et al.* Disentangling the contribution of multiple land covers to fire-mediated carbon emissions in Amazonia during the 2010 drought, *Global Biogeochemical Cycles*, v. 29, pp. 1739–1753, Oct. 2015.

[17] L. Poorter *et al.* Multidimensional tropical forest recovery, *Science*, v. 374, pp. 1370–1376, Dec. 2021.

[18] C. H. L. Silva-Junior *et al.* The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade, *Nature Ecology & Evolution*, v. 5, pp. 144–145, Feb. 2021.

[19] V. R. Pivello *et al.* Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies, *Perspectives in Ecology and Conservation*, v. 19, pp. 233–255, Jul. 2021.

[20] L. E. O. C. Aragão *et al.* 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions, *Nature Communications*, v. 9, p. 536, Dec. 2018.

[21] C. H. L. Silva-Junior *et al.* Fire Responses to the 2010 and 2015/2016 Amazonian Droughts, *Frontiers in Earth Science*, v. 7, pp. 1–16, May 2019.

[22] M. V. F. Silveira *et al.* Amazon fires in the 21st century: The year of 2020 in evidence, *Global Ecology and Biogeography*, v. 31, pp. 2026–2040, Oct. 2022.