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Carbon emissions from deforestation and forest fragmentation in the Brazilian Amazon

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Abstract

Forest-fragmentation-related edge effects are one of the major causes of forest degradation in Amazonia and their spatio-temporal dynamics are highly influenced by annual deforestation patterns. Rapid biomass collapse due to edge effects in forest fragments has been reported in the Brazilian Amazon; however the collective impacts of this process on Amazonian carbon fluxes are poorly understood. We estimated biomass loss and carbon emissions from deforestation and forest fragmentation related to edge effects on the basis of the INPE (Brazilian National Space Research Institute) PRODES deforestation data and forest biomass volume data. The areas and ages of edge forests were calculated annually and the corresponding biomass loss and carbon emissions from these forest edges were estimated using published rates of biomass decay and decomposition corresponding to the areas and ages of edge forests. Our analysis estimated carbon fluxes from deforestation (4195 Tg C) and edge forest (126–221 Tg C) for 2001–10 in the Brazilian Amazon. The impacts of varying rates of deforestation on regional forest fragmentation and carbon fluxes were also investigated, with the focus on two periods: 2001–5 (high deforestation rates) and 2006–10 (low deforestation rates). Edge-released carbon accounted for 2.6–4.5% of deforestation-related carbon emissions. However, the relative importance of carbon emissions from forest fragmentation increased from 1.7–3.0% to 3.3–5.6% of the respective deforestation emissions between the two contrasting deforestation rates. Edge-related carbon fluxes are of increasing importance for basin-wide carbon accounting, especially as regards ongoing reducing emissions from deforestation and forest degradation (REDD) efforts in Brazilian Amazonia.

Keywords: forest fragmentation, carbon emission, deforestation, Amazon

1. Introduction

Tropical forest clearing has been a major driver of biomass loss and atmospheric carbon emissions from land use (Canadell *et al* 2007, Le Quere *et al* 2009). Deforestation in Amazonia has played a particularly important role in the global carbon cycle in recent decades (Houghton *et al* 2000, DeFries *et al* 2002). Between the late 1990s and mid-2000s, annual deforestation rates climbed dramatically in the Brazilian Amazon in consequence of the vast expansion of croplands, predominantly soy plantation, and pasture during this period (Morton *et al* 2006, Nepstad *et al* 2006). Since 2006, however, annual deforestation rates have rapidly decreased due to declining product prices and the implementation of the Brazilian environmental laws that restrict deforestation through expansion of protected areas and the cancelation of credit for illegal land holdings (Nepstad *et al* 2008). By 2010, deforestation in the Brazilian Amazon reached its lowest rate in 22 years of monitoring (INPE 2010). This trend, with the potential for continued deforestation rate reductions (Nepstad *et al* 2009), suggests that carbon emissions from deforestation to the atmosphere may be reduced whereas other types of forest degradation increase in their relative importance for carbon monitoring in this region.

Forest fragmentation associated with human land use causes many changes in forest ecosystems, strongly affecting microclimates, tree mortality, carbon storage and faunal population dynamics (Laurance *et al* 2011). These factors may interact synergistically with anthropogenic-related activities such as hunting (Peres *et al* 2006), selective logging (Nepstad *et al* 1999), and fire (Cochrane 2001, Cochrane and Laurance 2002) that can result in biodiversity and forest structure degradation (Gardner *et al* 2009, Cochrane *et al* 1999). One of the most significant impacts of forest fragmentation is on carbon storage of forest fragments. Biomass of a forest fragment can be lost in two different ways: (1) biomass collapse due to the elevated rates of tree mortality near forest edges (Laurance *et al* 1997, 1998) and (2) by fire associated with increased flammability (Cochrane and Schulze 1999). In the case of fire, forest fragments have dry and fire prone edges and are juxtaposed with frequently brined pastures and regrowth (Uhl and Kauffman 1990, Nepstad *et al* 1999). In another case, field studies in central Amazonia have shown significant biomass loss near forest edges (Laurance *et al* 1997, Lovejoy *et al* 1986, Nascimento and Laurance 2004). A reduction of aboveground live biomass of 8–14% was found within 100 m of forest edges after fragmentation, with a rapid initial loss occurring during the first four years before biomass amounts stabilize at this lower amount (Laurance *et al* 1997). This type of biomass loss is caused by increased rates of tree mortality, damage and canopy-gap formation in fragments likely as a result of microclimate changes and increased wind turbulences and lianas proliferation near forest edges (Kapos 1989, Ferreira and Laurance 1997, Laurance *et al* 1997, 2001). Biomass collapse and subsequent decomposition has been postulated to be a potentially significant and unaccounted for source of atmospheric carbon in the tropics (Laurance *et al* 1998). A recent study from Rondônia in southwestern Amazonia, found that edge-related carbon emissions accounted for 3.6% of the total carbon fluxes related to deforestation over 25 years of land cover changes (Numata *et al* 2010). However, to date, there have been no basin-wide estimates of edge-related carbon fluxes that account for dynamic land cover change.

The process of biomass collapse and subsequent carbon emission from forest edges takes several years to be completed (Laurance *et al* 1998), therefore, potential edge-related biomass loss and carbon emissions are tightly related to both the extent of edge forest and the persistence of those forest edges over time (Numata *et al* 2010). Ongoing deforestation forms new edges and destroys old ones every year, therefore, the dynamics of forest edges (formation and loss of edges) are tightly associated with the spatial and temporal patterning and amounts of annual deforestation (Numata *et al* 2009).

In this study, we estimate carbon emissions from recent deforestation and edge-related biomass collapse due to forest fragmentation in the Amazon. We used the PRODES data, the digital map of annual deforestation of the Legal Amazon developed by the Brazilian National Space Research Institute (INPE), to estimate recent deforestation, forest fragmentation, biomass loss and carbon emissions from land cover changes for 2001–10. The PRODES digital map is developed from Landsat data and provides spatially explicit information on each year's deforested areas of the Legal Amazon since 2000 and has 120 m spatial resolution. Furthermore, to better ascertain the relative importance of forest fragmentation as a source of carbon emissions, we compared carbon fluxes of two different periods with contrasting land cover change trends, high (2001–5) and low (2006–10) deforestation rates, respectively.

2. Data and methods

The spatial information on deforestation in 2010 was only available in shape format at the time of our analysis, therefore we converted it into the raster format and then combined the 2010 deforestation with the 2000–9 PRODES digital map in order to quantify spatio-temporal changes in deforestation and forest fragmentation for the 2001–10 period. We considered all deforestation prior to 2001 as old deforestation and the forest edges belonging to this class were not included in our temporal analysis. The PRODES product used in this study covers 5150 242 km^2 of the Brazilian Amazon. There are some areas heavily affected by artifacts and errors apparently due to frequent cloudiness in the PRODES data, especially in a portion of the eastern Amazon region. These areas show unrealistic land cover change patterns such as the majority of deforestation occurring in a single year. Therefore, an area of 900 km^2 was eliminated from the analysis. Furthermore, PRODES deforested areas that did not have attribution to a specific year due to human misinterpretation, clouds or other problems were not included in this study. These areas accounted for 3.6% of the total deforestation. All forest edges generated by deforestation prior to 2001 were excluded from consideration due to the inability to determine the year of edge formation. As PRODES does not include secondary forest and vegetation in the Cerrado region, the land cover change associated with carbon emissions refers only to the conversion of primary forest to deforestation in this study.

To estimate annual biomass loss and carbon emissions from deforestation and forest fragmentation, we used a biomass map for the Brazilian Amazon generated by Sales (2010). The map was generated using geostatistical models based on data from 2300 one-hectare forest inventory plots collected during the RADAMBRASIL survey (DNPM 1978). The geostatistical model developed by Sales *et al* (2007) was used to create a 1 km^2 resolution timber volume map. Timber biomass values were converted to estimated forest biomass by applying expansion factors proposed by Nogueira *et al* (2008) that account for crown biomass in order to reduce the uncertainty in conversion of timber volume to biomass. Nogueira *et al* (2008) presented revised versions of the parameters originally developed by Brown and Lugo (1992), and corrected by Fearnside (1992), for converting timber volume values from RADAMBRASIL's inventories to biomass. Nogueira *et al* (2008) introduced a new VEF (volume expansion factor) parameter for dense forests, and new BEF (biomass expansion) parameters for both dense and open forests, which resulted in more accurate estimates of the

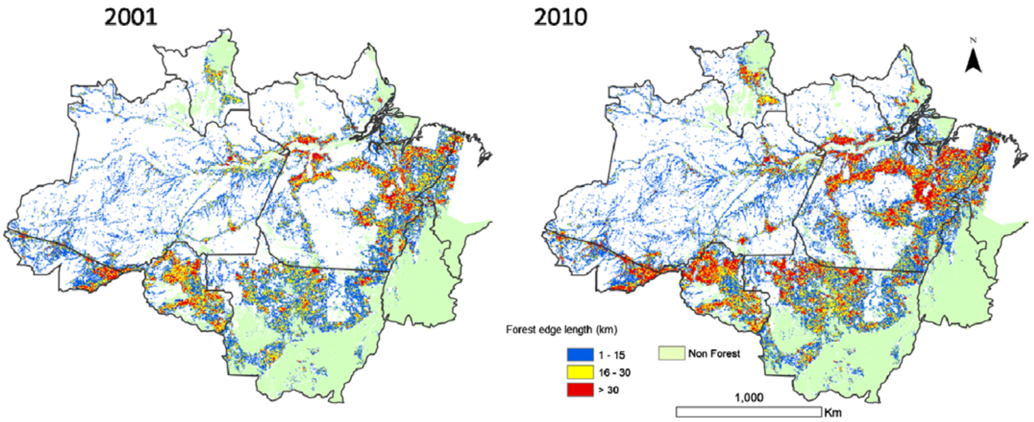

Figure 1. Forest fragmentation in the Brazilian Amazon in 2001 and 2010. Areas in different colors indicate the classes of total forest edge length (km) within each 5 km × 5 km grid cell.

biomass of forests when comparing to field data collected on both dense forests of Southern Amazon and open forests of Central Amazon. Biomass ranged from 49 to 559 Mg ha^{-1} with an average of 273 Mg ha^{-1}. More details are found in Sales *et al* (2007) and Sales (2010).

The calculation of annual biomass loss and carbon emissions from both deforestation and fragmentation were performed according to the methods used in Numata *et al* (2010). Estimated annual carbon emissions from deforestation were calculated using a book-keeping model, similar to Houghton *et al* (2000) and Ramankutty *et al* (2007). This model tracks the amount of carbon released to the atmosphere from clearing (burning) and decay of plant materials. In our estimate, the emissions and accumulations of carbon in regrowth and soils were not included. Deforested biomass was partitioned into the following fractions: biomass burnt ($f_{burn} = 0.2$), slash ($f_{slash} = 0.7$), long-lived wood products ($f_{prod} = 0.08$), and elemental carbon ($f_{elem} = 0.02$), in accordance with previous studies (Houghton *et al* 2000, Ramankutty *et al* 2007, Loarie *et al* 2009). Carbon from burned biomass is only released in the year of the deforestation event, while carbon from the other components is released over several years according to the established decay rates of 0.1 yr^{-1} for f_{slash} and $f_{product}$ and 0.001 yr^{-1} for f_{elem} (Houghton *et al* 2000). Carbon emission estimates from deforestation at any location, for a given year, were reduced, as needed, to account for carbon already fluxed from edges prior to their actual deforestation. Total live aboveground biomass loss due to deforestation (TDBL) was calculated as:

$$\mathrm{TDBL} = A_{def} \times \mathrm{bio} - \mathrm{BL}_{df\_aff}(t-1) \qquad (1)$$

where A_{def} is deforested area and bio is a specific biomass value (Mg ha^{-1}) to A_{def}, and $\mathrm{BL}_{df,aff}$ $(t-1)$ is biomass loss due to edge effects in edge-affected forest deforested in year t. According to this model, a portion of the biomass and carbon within an edge will have been lost prior to deforestation, with the amount depending on the age of the edge. This amount, therefore, should not be included in carbon emissions due to deforestation in a specific year.

For forest fragmentation, forest edges were delineated annually to quantify forest edge length (km) and biomass-collapse-affected forest was considered as a buffer zone of 120 m from forest edges (km^2). Figure 1 illustrates spatial variability of forest edges across the Brazilian Amazon in 2001 and 2010. Following the field studies of Laurance *et al* (1997, 1998), all significant live biomass collapse within the 120 m edge forests was modeled to occur over the first four years after any given edge forest's formation, with no further live biomass loss thereafter, unless subsequently deforested. In order to bracket the possible variation in biomass lost due to edge effects, we used a range of 8–14% of aboveground biomass lost in the first four years after forest fragmentation, corresponding to annual loss rates of 2.0–3.5% as per Laurance *et al* (1997).

Edge-related carbon emissions EC were estimated as follows:

$$\mathrm{EC} = A_{eaf} \times \mathrm{bio} \times \mathrm{Cr(age)} \times 0.5 \qquad (2)$$

where A_{eaf} is edge-affected forest area, bio is a specific biomass value for A_{eaf} and Cr is the carbon release rate for an edge of the given age, as explained below. Cr varies with edge age for as long as the edge persists. Biomass collapse emissions were estimated to occur at a constant decomposition rate of 10% yr^{-1}, following Fearnside (2000). Thus, any collapsed biomass carbon is emitted within ten years of falling and the whole carbon emission process for a new edge is completed over 13 years accounting for the time period of the collapse process. Edges older than 13 years have no net carbon flux to the atmosphere. Biomass carbon content was estimated as 50% (Fearnside *et al* 1993, Houghton *et al* 2000).

We estimated annual carbon emissions from forest edges for each year. However, since many edges are eliminated by subsequent deforestation, carbon emitted from those lost edges would eventually be accounted for by deforestation-based emission estimates. If edge forests are deforested soon after formation, the impacts of forest edges on regional carbon flux estimates will be small. Conversely, edge-related emissions gain in importance as average edge age increases.

We estimated carbon emissions from deforestation and fragmentation-related edge effects for three periods: (1) 2001–10, (2) 2001–5, and (3) 2006–10. For the 2006–10 period, we

Table 1. Summary of biomass loss and carbon emissions in the Amazon from both deforestation and forest fragmentation between 2001 and 2010. Values are subdivided by the periods 2001–5 and 2006–10, which had very different average annual deforestation rates. (Note: the number in parentheses refers to the amount of carbon emitted directly from areas deforested between 2006 and 2010.)

	2001–10	2001–5	2006–10
Deforestation			
Deforestation (km^2)	169 126	125 159	43 967
Average annual deforestation ($km^2\ yr^{-1}$)	16 912	25 032	8793
Biomass loss (Tg)	4195	3075	1120
Carbon emission (TgC)	1530	670	860 (260)
Fragmentation			
Edge forest (km^2)	66 149	51 075	15 073
Average annual edge gain/loss ($km^2\ yr^{-1}$)	8567/2170	12 566/2940	4568/1553
Biomass loss (Tg)	126–221	70–123	56.5–98.2, 31.3–55[a]
Carbon emission (TgC)	41.0–71.2	11.7–20.7	29.3–50.5, 5.7–10[a]
Edge C/total C (%)	2.6–4.5	1.7–3.0	3.3–5.6, 2.1–3.7[a]

[a] The values are relative to those from the edges created after 2005.

estimated carbon emissions for both: (a) older deforested areas (2001–5); and (b) newly deforested areas (2006–10). This allowed us to analyze the relative carbon emissions impacts of the very different deforestation rates that occurred in these two periods. Our analysis pertains only to effects of edge-related biomass collapse. We did not have the data to quantify other forms of forest degradation such as selective logging and forest fires that can occur along forest edges or in close proximity to deforestation. Both of these disturbances can remove or kill substantial proportions of the affected forests. The impacts of selective logging will vary according to extraction intensity and forest management practices (Uhl *et al* 1997, Nepstad *et al* 1999), while fire impacts will fluctuate with severity of burning that is most strongly associated with the number of times burned (Cochrane and Schulze 1999, Cochrane *et al* 1999). The carbon flux effects of these forest degradations will be additive with the estimates that we report here.

3. Results and discussion

Between 2001 and 2010, a total of 169 126 km^2 was deforested in the Brazilian Amazon, 74% occurred during 2001–05, and 26% during 2006–10 (table 1). Amazonian deforestation resulted in approximately 4190 Tg of live aboveground biomass loss that resulted in the release of 1530 TgC between 2001 and 2010. The average annual carbon emission of 153 TgC yr^{-1} is similar to previous estimates of the same region for the 1990s, 180 TgC yr^{-1} (Houghton *et al* 2000, DeFries *et al* 2002), 190 TgC yr^{-1} (with no inclusion of soil carbon emission) (Archard *et al* 2004) and more recently, 160 TgC yr^{-1} (Loarie *et al* 2009). Most slash and burn operations lead to incomplete combustion and, therefore, leave large residuals of dead biomass. Because of this, the majority of atmospheric carbon released due to Amazonian deforestation is actually coming from decaying biomass on the accumulated lands cleared prior to the current year's deforestation. Since our study period covers only ten years and ignores carbon emissions from areas deforested prior to 2001, deforestation-related emissions increase each year of the study period as the total post-2001 deforested area accumulates. For this reason,

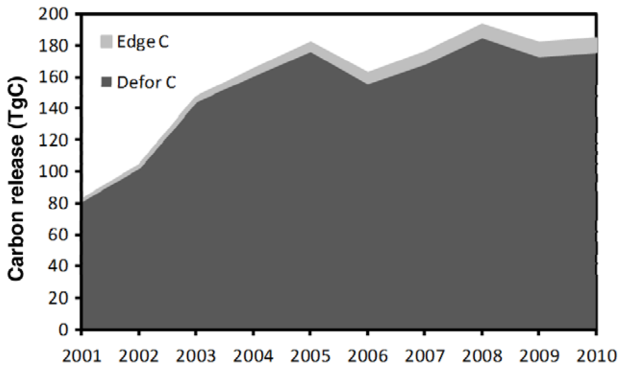

Figure 2. Annual carbon emissions from deforestation and forest edges for 2001–10.

deforestation-based carbon releases between 2006 and 2010 were much larger than those from 2001 to 2005, despite the large reduction in annual deforestation rates in recent years (figure 2). Conversely, the amount of live biomass lost in biomass collapse from edge effects, tracks directly with annual deforestation rates, and so, losses were much higher from 2001 to 2005 than 2006 to 2010. Carbon release from the actual areas deforested between 2006 and 2010 was 260 TgC, less than a half of 670 TgC emitted from areas deforested in 2001–5 (table 1).

Edge forests are concentrated over an arc extending from the southwest to the northeast Brazilian Amazon, including the states of Acre, Rondônia, Mato Grosso and Pará (figure 1). As of 2010, there were 66 149 km^2 of edge forests, accounting for 2.8% of remaining forest. Of these, most edge forests were generated between 2001 and 2005 (77%), with 23% between 2006 and 2010. The edge formation process is a dynamic balance between new edge creation and older edge destruction. From 2001 to 2010, new edge creation rates averaged 8567 $km^2\ yr^{-1}$, while edge destruction rates average 2170 $km^2\ yr^{-1}$. From 2001 to 2005, 12 566 $km^2\ yr^{-1}$ of edge forest was formed and 2940 km^2 of edge forests were lost annually, whereas much lower edge formation (4568 $km^2\ yr^{-1}$) and edge erosion rates (1553 $km^2\ yr^{-1}$) characterized 2006–10.

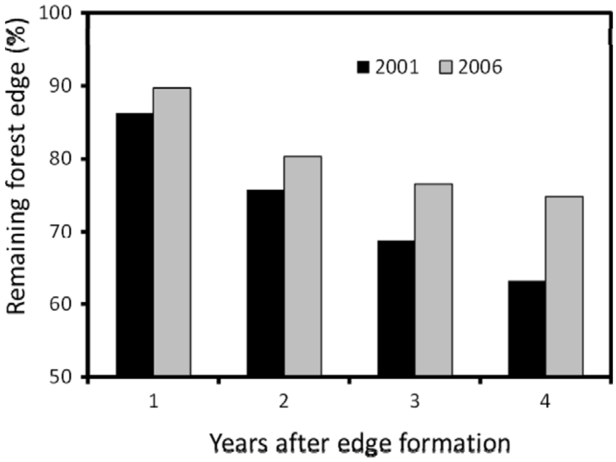

Figure 3. Changes in the percentage of remaining forest edges that were formed in either 2001 or 2006 over time as functions of ongoing basin-wide deforestation in subsequent years.

The reduction of deforestation rates between the 2001–5 and 2006–10 time periods has affected the dynamics of forest edges. Specifically, edge forest formation rates were reduced substantially while the persistence of existing edges was extended. For example, only 62% of forest edges created in 2001 remained in 2005. However, 75% of forest edges created in 2006 remained by 2010 (figure 3). Longer periods of edge exposure result in more carbon emissions from forest edges that are unaccounted for in current, deforestation-based estimates of carbon fluxes. Edge ages increase as frontier regions get older and landscape dynamics decrease (Numata *et al* 2009), as well as in regions where they abut against functioning protected areas (Barber *et al* 2011). If they persist, the currently low deforestation rates will eventually result in substantial carbon emission reductions from both deforestation and forest edges. However, the relative importance of unaccounted for edge-related carbon fluxes to total carbon emissions will increase during this period of change.

During the 2001–10 interval, we estimate that each year an average of 4.0–7.1 TgC of unaccounted for carbon was emitted from forest edges (figure 2). Unaccounted edge-related carbon releases were 1.7–3.0% (2001–5) and grew to 3.3–5.6% (2006–10) of the respective deforestation emissions during these intervals. From 2001 to 2010, unaccounted edge-related carbon emissions (41.0–71.5 TgC) equate to 2.7–4.7% of deforestation-related emissions. Due to the ever growing amount of forest edges and the declining rate of their deforestation, edge-related carbon releases were much greater during the 2006–10 (29–51 TgC) period than the 2001–5 (12–21 TgC) interval. However, only 5.7–10 TgC was emitted from forest edges newly formed during 2006–10. The current trend of decreasing deforestation rates may continue in the coming years as the Brazilian government has committed to reducing deforestation to 20% of the average 1996–2005 rate by 2020 (Alexandratos 2006), a reduction from nearly 20 000 to 4000 km^2 yr^{-1}. If this goal is accomplished, a massive amount of potential carbon emissions from deforestation, equivalent to more than 10% of annual global emissions from land use for the 2000–6 period, would be reduced in the Amazon (Canadell *et al* 2007, Nepstad *et al* 2009). These goals do not seem unrealistic. As of 2010, deforestation was already 67 % below the reference rate (INPE 2010). Achieving the goal of 80% deforestation rate reductions in the Amazon would require considerably less drastic land cover changes by 2020 than have already occurred between 2005 and 2010. If deforestation were to stop completely in 2010, with no further forest edge dynamics (i.e., the maximum persistence of forest edges in the landscape), cumulative carbon emissions from slash decomposition in deforested areas and forest edges would total another 556 TgC and 32.2–56.4 TgC by 2020, respectively. Edge-related carbon would account for additional 3.1–5.4% over the total carbon emission from deforestation by 2020. In a stabilized landscape, however, the growing importance of carbon fluxes from edge forests would be temporary because the majority of decomposition of the collapsed biomass would occur within 10–13 years after formation (Laurance *et al* 1998).

There are some sources of uncertainty to be addressed in our analysis. For the estimates of carbon emissions from deforestation, the actual rates of carbon emission will vary according to each land use type (e.g. pasture, soybean, other crop types) and landowner-dependent land management practices that alter the frequency, fuel consumption and intensity of human-induced fires (Ramankutty *et al* 2007, Kauffman *et al* 2009, Galford *et al* 2011). However, since no spatially explicit maps of land use types exist for the Brazilian Amazon, in this analysis, we treated all deforested areas as a single land use type and made use of published rates of annual carbon emissions in the book-keeping model (sensu Houghton *et al* 2000). For the estimates of carbon emission from forest edges, while our estimates were based upon a single landscape (Laurance *et al* 1997), the variability of the biomass collapse rates across the Amazon region is uncertain. Another point is the potential increase in forest biomass since the 1970's RADAMBRASIL forest inventory. Tree growth may increase Amazonian forest biomass by nearly 1.0 Mg ha^{-1} yr^{-1} (Phillips *et al* 1998), potentially adding as much as 30 Mg ha^{-1} (roughly 10%) to all forest biomass values used in this study. Since the spatial variability of tree growth rates is not well known, we did not incorporate this potential biomass increase into account in our analysis but such factors should be considered in future analyses.

4. Conclusions

Until now, regional carbon fluxes from biomass collapse within dynamic edge structures of remaining Amazonian forests have been poorly quantified. Our results show that the unaccounted carbon release from forest edges likely resulted in additional carbon emissions equivalent to 3.5% (2.6–4.5%) of that from deforestation alone for 2001–10. Previous estimates of the net carbon release from forest degradation (selective logging and wildfire) indicate that these forest degradations may account for up to 7% (Nepstad *et al* 1999) of Amazonian carbon losses, therefore, the combined carbon emissions from these forest disturbances and fragmentation-related edge effects may exceed 10% of deforestation-based carbon flux estimates. With the recent drop in deforestation rates, the unaccounted proportion of edge-related carbon within the total carbon emissions from the Amazon may continue to grow as a function of longer edge persistence on the landscape, despite a much smaller potential overall carbon release from land cover change. Furthermore, the exposure of forest edges for longer periods may increase the risk of suffering larger scale edge effects and synergistic interactions between fires, forest fragmentation and climate change, which could further increase carbon emissions from these forests (Cochrane and Laurance 2008). With the increased accuracies necessary for carbon accounting in Reducing Emissions from Deforestation and Forest Degradation (REDD) projects, it is necessary to track dynamic processes such as forest edge formation and destruction to precisely ascertain both the spatial and temporal fluxes of carbon. Similarly, based on our analyses, efforts to maximize landscape-level carbon retention should emphasize maintenance of larger contiguous blocks of forest over highly fragmented forest landscapes wherever practicable. Taking such factors into account will not only lead to better overall quantification of carbon fluxes but also change incentives for the management of land use and landscape configurations.

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References

Alexandratos N 2006 *World Agriculture: Towards 2030/2050* (Rome: Global Perspective Studies Unit, Food and Agriculture Organization of the United Nations)

Archard F, Eva H D, Mayaux P, Stibig H J and Belward A 2004 Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s *Glob. Biogeochem. Cycl.* **18** GB2008

Barber C P, Cochrane M A, Souza C and Veríssimo A 2011 Dynamic performance assessment of protected areas *Biol. Conserv.* at press

Brown S and Lugo A 1992 Aboveground biomass estimates for tropical moist forest of the Brazilian Amazon *Interciencia* **17** 8–18

Canadell J G, Le Quere C, Raupach M R, Field C B, Buitenhuis E T, Ciais P, Conway T J, Gillett N P, Houghton R A and Marland G 2007 Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks *Proc. Natl Acad. Sci.* **104** 18866–70

Cochrane M A 2001 Synergistic interactions between habitat fragmentation and fire in evergreen tropical forests *Conserv. Biol.* **15** 1515–21

Cochrane M A, Alencar A, Schulze M D, Souza C M Jr, Nepstad D C, Lefebvre P and Davidson E 1999 Positive feedbacks in the fire dynamic of closed canopy tropical forests *Science* **284** 1832–5

Cochrane M A and Laurance W F 2002 Fire as a Large-scale edge effect in Amazonian forests *J. Trop. Ecol.* **18** 311–25

Cochrane M A and Laurance W F 2008 Synergisms among fire, land use, and climate change in the amazon *Ambio* **37** 522–7

Cochrane M A and Schulze M D 1999 Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition *Biotropica* **31** 2–16

DeFries R S, Houghton R A, Hansen M C, Field C B, Skole D and Townshend J 2002 Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s *Proc. Natl Acad. Sci. USA* **99** 14256–61

DNPM (Departamento Nacional de Prodção Mineral) 1978 *Projeto RADAMBRASIL: Levantamento de Recursos Naturais* (Rio de Janeiro: Ministério das Minas e Energia)

Fearnside P M 2000 Greenhouse gas emissions from land-use change in Brazil's Amazon region *Glob. Clim. Change Trop. Ecosyst.* 231–49

Fearnside P M 1992 Forest biomass in Brazilian Amazonia: comments on the estimate by Brown and Lugo *Interciencia* **17** 19–27

Fearnside P M, Leal N and Fernandes F M 1993 Rain forest burning and the global carbon budget—biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon *J. Geophys. Res.—Atmos.* **98** 16733–43

Ferreira L V and Laurance W F 1997 Effects of forest fragmentation on mortality and damage of selected trees in central Amazonia *Conserv. Biol.* **11** 797–801

Galford G L *et al* 2011 Historical carbon emissions and uptake from the agricultural frontier of the Brazilian Amazon *Ecol. Appl.* **21** 750–63

Gardner T A, Barlow J, Chazdon R, Ewers R, Harvey C A, Peres C A and Sodhi N S 2009 Prospects for tropical forest biodiversity in a human-modified world *Ecol. Lett.* **12** 561–82

Houghton R A, Skole D L, Nobre C A, Hackler J L, Lawrence K T and Chomentowski W H 2000 Annual fluxes or carbon from deforestation and regrowth in the Brazilian Amazon *Nature* **403** 301–4

INPE 2010 *PRODES—Desflorestamento nos Municipios* (São José dos Campos: Instituto National de Pesquisas Espaciais)

Kapos V 1989 Effects of isolation on the water status of forest patches in the Brazilian Amazon *J. Trop. Ecol.* **5** 173–85

Kauffman J B, Hughes R F and Heider C 2009 Carbon pool and biomass dynamics associated with deforestation, land use, and agricultural abandonment in the neotropics *Ecol. Appl.* **19** 1211–22

Laurance W, Cochrane M, Bergen S, Fearnside P M, Delamonica P, Barber C, D'Angelo S and Fernandes T 2001 The future of the Brazilian Amazon *Science* **291** 438–9

Laurance W, Laurance S and Delamonica P 1998 Tropical forest fragmentation and greenhouse gas emissions *For. Ecol. Manage.* **110** 173–80

Laurance W F, Laurance S G, Ferreira L V, RankindeMerona J M, Gascon C and Lovejoy T E 1997 Biomass collapse in Amazonian forest fragments *Science* **278** 1117–8

Laurance W F *et al* 2011 The fate of Amazonian forest fragments: a 32-year inverstigation *Biol. Conserv.* **144** 56–67

Le Quere C *et al* 2009 Trends in the sources and sinks of carbon dioxide *Nature Geosci.* **2** 831–6

Loarie S R, Asner G P and Field C B 2009 Boosted carbon emissions from Amazon deforestation *Geophys. Res. Lett.* **36** L14810

Lovejoy T E, Bierregaard R O, Rylands A B, Malcolm J R, Quintela C, Harper L, Brown K, Powell A, Powell G, Schubart H and Hays M 1986 Edge and other effects of isolation on Amazon forest fragments *Conservation Biology: The Science of Scarcity and Diversity* ed M E Soulé (Sunderland, MA: Sinauer) pp 257–85

Morton D C, DeFries R S, Shimabukuro Y E, Anderson L O, Arai E, Espirito-Santo F D, Freitas R and Morisette J 2006 Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon *Proc. Natl Acad. Sci. USA* **103** 14637–41

Nascimento H E M and Laurance W F 2004 Biomass dynamics in Amazonian forest fragments *Ecol. Appl.* **14** S127–38

Nepstad D C, Stickler C M and Almeida O T 2006 Globalization of the Amazon soy and beef industries: opportunities for conservation *Conserv. Biol.* **20** 1595–603

Nepstad D C, Stickler C M, Soares B and Merry F 2008 Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point *Phil. Trans. R. Soc.* B **363** 1737–6

Nepstad D C *et al* 1999 Large-scale impoverishment of Amazonian forests by logging and fire *Nature* **398** 505–8

Nepstad D C *et al* 2009 The end of deforestation in the Brazilian Amazon *Science* **326** 1350–1

Nogueira E, Fearnside P and Nelson B 2008 Estimates of forest biomass in the Brazilian Amazon: new allometric equations and adjustments to biomass from wood-volume inventories *For. Ecol. Manage.* **256** 1853–67

Numata I, Cochrane M A, Roberts D A and Soares J V 2009 Determining dynamics of spatial and temporal structures of forest edges in South Western Amazonia *For. Ecol. Manage.* **258** 2547–55

Numata I, Cochrane M A, Roberts D A, Soares J V, Souza C M and Sales M H 2010 Biomass collapse and carbon emissions from forest fragmentation in the Brazilian Amazon *J. Geophys. Res.—Biogeosci.* **115** G03027

Peres C A, Barlow J and Laurance W F 2006 Detecting anthropogenic disturbance in tropical forests *Trends Ecol. Evol.* **21** 227–9

Phillips O L *et al* 1998 Changes in the carbon balance of tropical forest: evidence from long-term plots *Science* **282** 439–42

Ramankutty N, Gibbs H, Achard F, Defriess R, Foley J and Houghton R 2007 Challenges to estimating carbon emissions from tropical deforestation *Glob. Change Biol.* **13** 51–66

Sales M H 2010 Estimating interpolation uncertainty of forest biomass stocks and carbon emissions from deforestation in the Brazilian Amazon using inventory data and geostatistics *Master Thesis* University of California Santa Barbara

Sales M H, Souza C M, Kyriakidis P C, Roberts D A and Vidal E 2007 Improving spatial distribution estimation of forest biomass with geostatistics: a case study for Rondonia, Brazil *Ecol. Modelling* **205** 221–30

Uhl C, Barreto P, Veríssimo A, Vidal E, Amaral P, Barros A C, Souza C, Johns J and Gerwing J 1997 Natural resource management in the Brazilian Amazon *Bioscience* **47** 160–8

Uhl C and Kauffman J B 1990 Deforestation, fire susceptibility, and potential tree responses to fire in the Eastern Amazon *Ecology* **71** 437–49