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 burned 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 5150242 km² 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 km² 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 km² 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
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 \((f_{\text{burn}} = 0.2)\), slash \((f_{\text{slash}} = 0.7)\), long-lived wood products \((f_{\text{prod}} = 0.08)\), and elemental carbon \((f_{\text{elem}} = 0.02)\), 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 \(f_{\text{slash}}\) and \(f_{\text{prod}}\) and 0.001 yr\(^{-1}\) for \(f_{\text{elem}}\) (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:

\[
\text{TDBL} = A_{\text{def}} \times \text{bio} - B_{\text{def,aff}}(t - 1)
\]

where \(A_{\text{def}}\) is deforested area and bio is a specific biomass value (Mg ha\(^{-1}\)) to \(A_{\text{def}}\), and \(B_{\text{def,aff}}(t - 1)\) 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:

\[
EC = A_{\text{eff}} \times \text{bio} \times Cr(\text{age}) \times 0.5
\]

where \(A_{\text{eff}}\) is edge-affected forest area, bio is a specific biomass value for \(A_{\text{eff}}\) 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...
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 km² 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, 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 from 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 km² 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 km² yr⁻¹, while edge destruction rates average 2170 km² yr⁻¹. From 2001 to 2005, 12 566 km² yr⁻¹ of edge forest was formed and 2940 km² of edge forests were lost annually, whereas much lower edge formation (4568 km² yr⁻¹) and edge erosion rates (1553 km² yr⁻¹) characterized 2006–10.

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 (km²)     | 169 126        | 125 159        | 43 967          |
| Average annual deforestation (km² yr⁻¹) | 16 912        | 25 032         | 8793            |
| Biomass loss (Tg)       | 4195           | 3075           | 1120            |
| Carbon emission (TgC)   | 1530           | 670            | 860 (260)       |
| **Fragmentation**       |                |                |                 |
| Edge forest (km²)       | 56 566         | 11 707         | 29 305          |
| Average annual edge gain/loss (km² yr⁻¹) | 5 667/21 700 | 12 566/29 400 | 45 68/1 553     |
| Biomass loss (Tg)       | 126–221        | 70–123         | 56.5–98.2, 31.3–55a |
| Carbon emission (TgC)   | 41.0–71.2      | 11.7–20.7      | 29.3–50.5, 5.7–10a |
| Edge C/total C (%)      | 2.6–4.5        | 1.7–3.0        | 3.3–5.6, 2.1–3.7 |

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

Figure 2. Annual carbon emissions from deforestation and forest edges for 2001–10.
more than 10% of annual global emissions from land use for
of potential carbon emissions from deforestation, equivalent to
ongoing basin-wide deforestation in subsequent years.

Changes in the percentage of remaining forest edges that
were formed in either 2001 or 2006 over time as functions of
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 km² 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
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