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Biomass collapse and carbon emissions from forest fragmentation in the Brazilian Amazon

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[1] Forest fragmentation due to deforestation is one of the major causes of forest degradation in the Amazon. Biomass collapse near forest edges, especially within 100 m, alters aboveground biomass and has potentially important implications for carbon emissions in the region. This phenomenon is tightly linked to spatial and temporal dynamics of forest edges in a landscape. However, the potential biomass loss and carbon emissions from forest edges and these spatiotemporal changes have never been estimated for actual landscapes in the Amazon. We conducted a deep temporal analysis of Rondônia, southwestern Brazilian Amazonia, using six Landsat path-row scenes covering the 1985–2008 time period to estimate annual biomass loss and associated carbon emissions within 100 m of forest edges. Annual edge biomass loss averaged 9.1% of the biomass loss from deforestation during the study period, whereas average annual edge-related carbon emissions from biomass loss were 6.0% of deforestation-derived carbon emissions. However, because many edges were subsequently deforested during the 24 year study period, actual unaccounted for edge-related carbon emissions during the 1985–2008 period, calculated from edges of all ages extant on the landscape in 2008, amounted to 3.6% of that attributed to all deforestation-derived carbon fluxes for this time interval. Biomass loss and carbon emissions are highly influenced by the extent and age of edge-affected forests. Large annual contributions of biomass loss and carbon emissions were found from active deforestation regions with young edges, whereas regions dominated by older edges had lower biomass loss and carbon emissions from edges.

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1. Introduction

[2] Deforestation has been a major driver of reducing forest biomass and changing carbon fluxes in Amazonia. Biomass loss and associated carbon emissions are also caused by forest degradation. Monitoring both deforestation and degradation is necessary to improve estimates of carbon fluxes [*Global Observation of Forest and Land Cover Dynamics*, 2008]. Although carbon fluxes from deforestation have been studied for the tropics [*Houghton*, 1999; *Houghton et al.*, 2000; *DeFries et al.*, 2002; *Achard et al.*, 2002, 2004], carbon fluxes from forest degradation remain uncertain.

[3] The process of biomass collapse in forest edges, resulting from forest fragmentation, could be an important source of atmospheric carbon. Field studies in central Amazonia have shown significant biomass loss due to increased rates of tree mortality and damage near forest edges [*Lovejoy et al.*, 1986; *Ferreira and Laurance*, 1997; *Laurance et al.*, 1997; *Nascimento and Laurance*, 2004]. A loss of aboveground live biomass of 8%–14% was found within 100 m of forest edges for during the first 7–10 years after fragmentation, with a rapid initial loss occurring over the first 4 years [*Laurance et al.*, 1997]. There is an emerging concern that the process of edge-related biomass collapse could be an important but unaccounted source of atmospheric carbon [*Laurance et al.*, 1998].

[4] Although carbon emissions from other forest degradation processes, such as selective logging and fire, have been estimated [*Nepstad et al.*, 1999; *van der Werf et al.*, 2003; *Guild et al.*, 2004] and considered in carbon models [*Houghton et al.*, 2000; *DeFries et al.*, 2002], carbon emissions from biomass collapse caused by edge effects are currently unaccounted for in carbon dynamic studies. As deforestation continues because of rapid regional develop-

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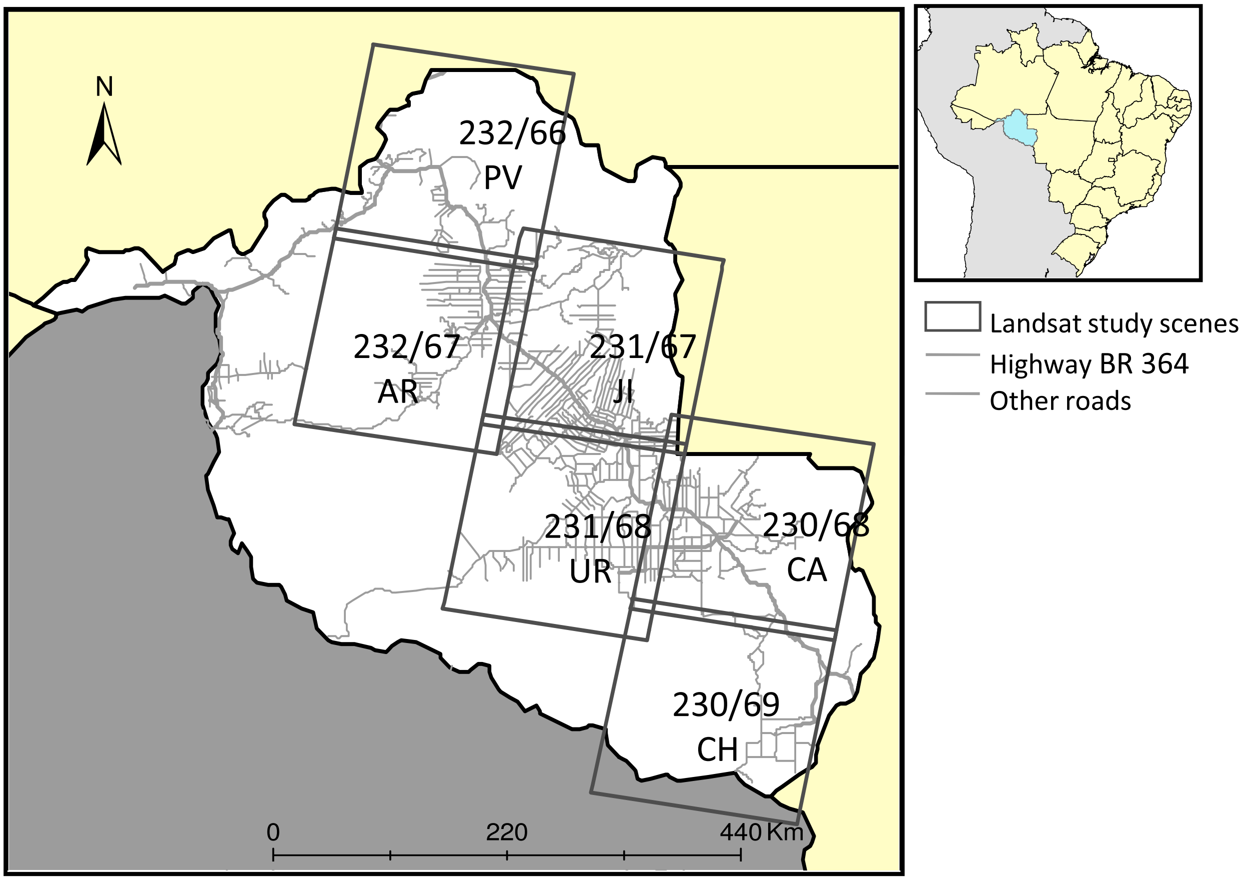

Figure 1. Study region, the state of Rondônia, and six Landsat scenes studied: 232/66 (Porto Velho, PV), 232/67 (Ariquemes, AR), 231/67 (Ji-Parana, JI), 231/68 (Urupa, UR), 230/68 (Cacoal, CA), and 230/69 (Chupinguaia, CH).

ment, more and more tropical forest will be fragmented and this degradation process may become increasingly important for carbon accounting.

[5] Results of different simulation models suggest that estimates of carbon emissions from biomass collapse are highly variable, varying with the amount and spatial patterns of clearing [*Laurance et al.*, 1998]. The impact of biomass collapse and associated carbon emissions is also influenced by the persistence or age of edge-affected areas since the processes of biomass collapse in forest edges and subsequent decomposition of biomass for carbon release take several years. Real landscapes are mosaics of different-aged forest fragments, created as ongoing deforestation processes both create new edges and eliminate older edges every year [*Numata et al.*, 2009]. This dynamic process further complicates the estimation of biomass loss and associated carbon release over time. Under intensive deforestation, many edges can be eroded before biomass collapse is even completed. However, it is not clear how the extent and dynamics of edge-affected forest and their edge age composition change over time and how they affect biomass and carbon loss at landscape and regional scales. Important questions include (1) what is the variability in biomass loss and carbon emissions in space and time; (2) when and where is emission largest and becomes critical?; and (3) what is the amount of biomass loss associated with edge effects, and how does it compare to deforestation? These questions regarding the impacts of forest fragmentation on biomass loss and carbon flux remain unanswered. To accurately estimate biomass loss and potential carbon emissions from real landscapes, it is necessary to have detailed spatial and temporal information of the forest edges.

[6] We evaluated the hypothesis that biomass collapse is an important and unaccounted source of biotic carbon in the Brazilian Amazon. The goal of this study is to estimate the magnitude of the potential biomass loss and the total net flux of carbon from biomass collapse because of forest fragmentation, based upon the findings of *Laurance et al.* [1997]. We used 25 years of annual satellite imagery to identify dynamics of forest edges, edge-affected forest area and the composition of edge ages each year. On the basis of these data, we estimated annual biomass loss and carbon release in the state of Rondônia in the southwest Brazilian Amazon.

2. Study Region

[7] Our study region consists of six Landsat scenes covering 68% of the state of Rondônia and some small portions of the surrounding states (Figure 1). Land cover conversion in Rondônia began with the construction of the federal highway BR364 and establishment of rural settlement to

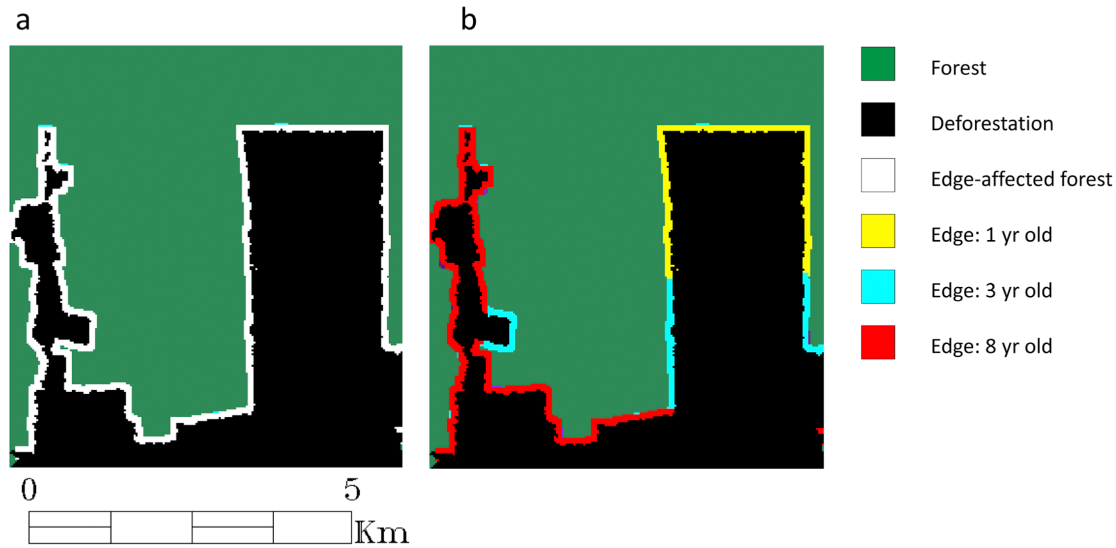

Figure 2. Illustration of forest edges. (a) Remaining forest, deforestation, and edge-affected forest. (b) Edge-affected forests with different edge ages.

agrarian reform back in the late 1960s [*Pedlowski et al.*, 1997]. The expansion of secondary roads with the rural settlements contributed greatly to high deforestation rates and consequent forest fragmentation in this region. By 2008, the total deforested area reached more than 20% of the state and the annual deforestation rate remains high, averaging 2658 km^2 yr^{-1} between 2001 and 2008 [Instituto Nacional de Pesquisas Espaciais, *INPE*, 2010].

[8] In terms of environmental variability of this region, annual rainfall averages between 1930 and 2690 mm/yr and varies spatially from highs in the northwest to lows in the southeast. The average temperature is 24°C, whereas relative humidity varies between 80% and 85% with a well-defined dry season during July and August. Natural vegetation is dominated by upland "terra firme" forests; some savanna regions and transitional forests are located in central and southern portions of the state [*RADAM BRASIL*, 1978].

3. Methods

[9] The Landsat scenes of our study region include 232/66 (Porto Velho, PV), 232/67 (Ariquemes, AR), 231/67 (Ji-Parana, JI), 231/68 (Urupa, UR), 230/68 (Cacoal, CA), and 230/69 (Chupinguaia, CH) (Figure 1). Each scene provides a complete 25 year annual time series data set between 1984 and 2008. Biomass loss and associated carbon emissions from edges vary as a function of time since forest fragmentation, extent of edge-affected forest, and vegetation aboveground biomass [*Laurance et al.*, 1997, 1998; *Numata et al.*, 2009]. To quantify biomass loss and carbon release from edges annually, we used two main data sources, an age map since deforestation and an aboveground live biomass distribution map.

[10] To create the age map, multitemporal land cover maps generated from Landsat time series data using the methodology of *Roberts et al.* [1998, 2002] were used. The age map was used to compute edge-affected forest areas and forest edge ages, i.e., the periods of time since edge creation because of deforestation, for each year during the study period. Figure 2 illustrates these measures. Edge-affected forest areas were considered as a buffer zone of 90 m from forest edges (Figure 2a). As edge-affected forest areas are composed of a mosaic of different edge ages (Figure 2b) and their composition changes every year because of ongoing deforestation, the annual edge-affected areas of all different ages were also quantified. More details about the calculation of edge-affected forest areas and composition of edge ages are described in the study by *Numata et al.* [2009]. These measurements were calculated from 1985 to 2008, and those areas that were either deforested or had forest edges before 1985 were eliminated from the analysis because of the lack of land cover change history. The 1984 land cover map was used to identify all deforested areas before 1985, considered as "pre-1985 deforestation" and also associated edge-affected areas before 1985. Other nonforest land cover types (e.g., savanna/rocks and water) were masked out of all images. Pre-1985 deforestation accounted for 8.5% and pre-1985 edge-affected forest area was 8.1% within the entire study area (the six Landsat scenes).

[11] The mean aboveground biomass distribution map, developed by *Sales et al.* [2007] for the state of Rondônia, was used as an input of base biomass data for the estimates of annual biomass loss and carbon emissions. This biomass map was developed by using geostatistic models combining 330 one hectare plots from the RADAM BRASIL survey conducted in the 1970s within and along areas adjacent to the state of Rondônia. The biomass ranges from 225 to 486 Mg/ha^{-1} with 1 km^2 resolution pixel size. More details are given by *Sales et al.* [2007]. All spatial and temporal analyses of satellite data were performed using the Interactive Data Language (ITT).

[12] We calculated annual biomass loss and carbon emissions from both deforestation and fragmentation in the period between 1985 and 2008, based upon the age maps and the aboveground biomass map described above. According to *Laurance et al.* [1997], an average loss of

aboveground biomass equal to 8.8% occurred within 100 m of a forest edge. Most biomass collapse occurs over 6–9 years with the pronounced decay in the first 3–4 years due to an abrupt increase of tree mortality after forest fragmentation [*Lovejoy et al.*, 1986; *Laurance*, 1997; *Ferreira and Laurance*, 1997]. Some trees are also damaged due to wind throw [*Ferreira and Laurance*, 1997]. Hence, in our analysis, we assume the 10.6% aboveground biomass is lost (8.8% from tree mortality and 1.8% from tree damage; *Laurance et al.* [1997, 1998]) within edge-affected forests (100 m from edge) during 4 years after forest fragmentation. To account for yearly losses, annual losses were distributed equally over 4 years, equal to 2.65% yr^{-1} when applied to the initial biomass within an edge following forest fragmentation (2.65% × 4 = 10.6%). We considered the initial and most significant biomass collapse as given by *Laurance et al.* [1997]. Therefore, no biomass loss was considered after 4 years. The amount of edge-biomass loss (EBL) in landscapes varies as a function of extent of edge-affected forests and aboveground biomass of forests, but the decay rate is constant during the first four years. For the calculation of annual EBL, the affected ages of forest edges will vary from 1 to 4 years, whereas initial biomass amounts of forest edges will vary according to the corresponding biomass values from the biomass map. The following formula was used in EBL calculation:

$$\mathrm{EBL}_{\mathrm{age}} = A_{\mathrm{eaf}}\,\mathrm{bio}\,0.0265 \ \text{for}\ 1 \geq \mathrm{age} < 4 \tag{1a}$$

$$\mathrm{EBL}_{\mathrm{age}} = 0 \ \text{for all age} > 4, \tag{1b}$$

where A_{eaf} is edge-affected forest area of a specific biomass value bio (Mg ha^{-1}), from the study by *Sales et al.* [2007] and changes at a constant rate for edge ages (age) of 1–4 years before stabilizing at zero for ages greater than 4 [*Laurance et al.*, 1998]. The value 0.0265 is the annual decay rate of biomass discussed above.

[13] Calculation of carbon release from biomass collapse in forest edges is similar to EBL, but the process of carbon release is longer than the biomass collapse. It was estimated as below

$$\mathrm{EC} = A_{\mathrm{eaf}}\mathrm{bio}^{*}\mathrm{Cr}(\mathrm{age})\,0.5, \tag{2}$$

where Cr is the carbon release rate for age, as explained below. The rate of carbon release varies according to edge ages. We considered that carbon is emitted from biomass collapse at a constant decomposition amount in each cohort, i.e., 10% yr^{-1} of the original collapsed biomass, and all carbon is emitted within 10 years in each cohort, as per the study by *Fearnside* [2000]. Thus, the whole carbon emission process is completed in 13 years after forest fragmentation. Hence, we assumed that those edges older than 13 years do not add any net carbon to the atmosphere. The carbon content of biomass was estimated as 50% [*Fearnside et al.*, 1993; *Houghton et al.*, 2000].

[14] Total live aboveground biomass loss due to deforestation was calculated as

$$\mathrm{TDBL} = A_{\mathrm{def}}\mathrm{bio} - \mathrm{BL}_{\mathrm{df\_aff}}(t-1). \tag{3}$$

$\mathrm{BL}_{\mathrm{df,aff}}\,(t-1)$ 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 should not be included in the biomass loss due to deforestation in a specific year.

[15] The estimate of annual carbon emissions from deforestation was based upon a book-keeping model similar to that of *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 material as well as the amount of carbon accumulated as regrowth. In our estimate, the emissions and accumulations of carbon in regrowth and soils were not included. The biomass cleared by deforestation is partitioned into the following fractions: biomass burnt (f_{burn} = 0.2), slash(f_{slash} = 0.7), product pools (f_{prod} = 0.08), and elemental carbon (f_{elem} = 0.02). Carbon from biomass burnt is released in the year of deforestation, whereas carbon from the other components is released for several years according to different decay rates. We assumed a decay rate 0.1 yr^{-1} for f_{slash} and f_{product} and a decay rate of 0.001 yr^{-1} for f_{elem} as used by *Houghton et al.* [2000]. Estimates of carbon emissions from deforestation for a given year were reduced by the amount of C already fluxed from edges before their actual deforestation.

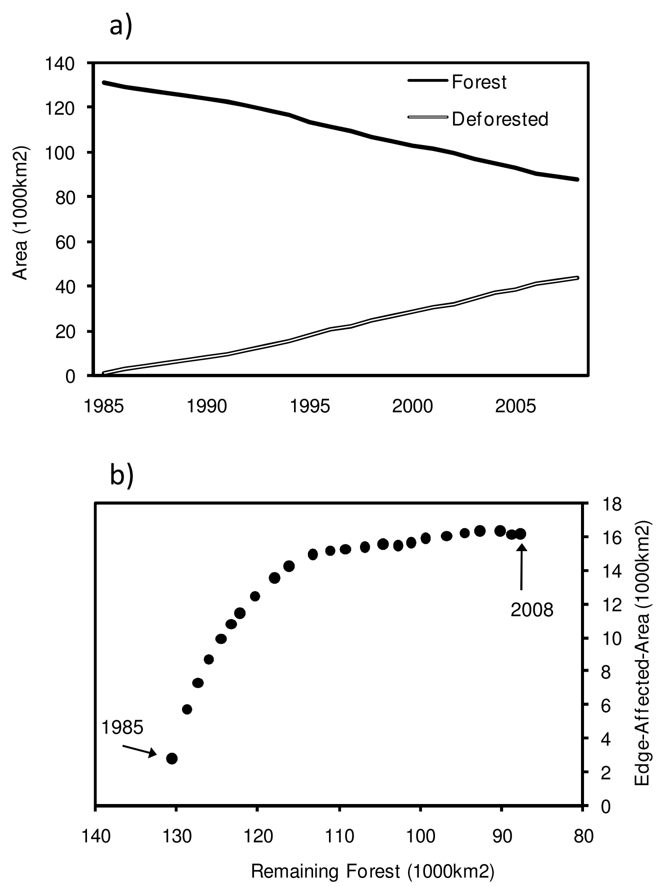

Figure 3. (a) Changes in remaining forests and deforestation and (b) dynamics of edge-affected forest area as a function of remaining forest area. Each dot refers to a year of the study period (1985–2008, left to right).

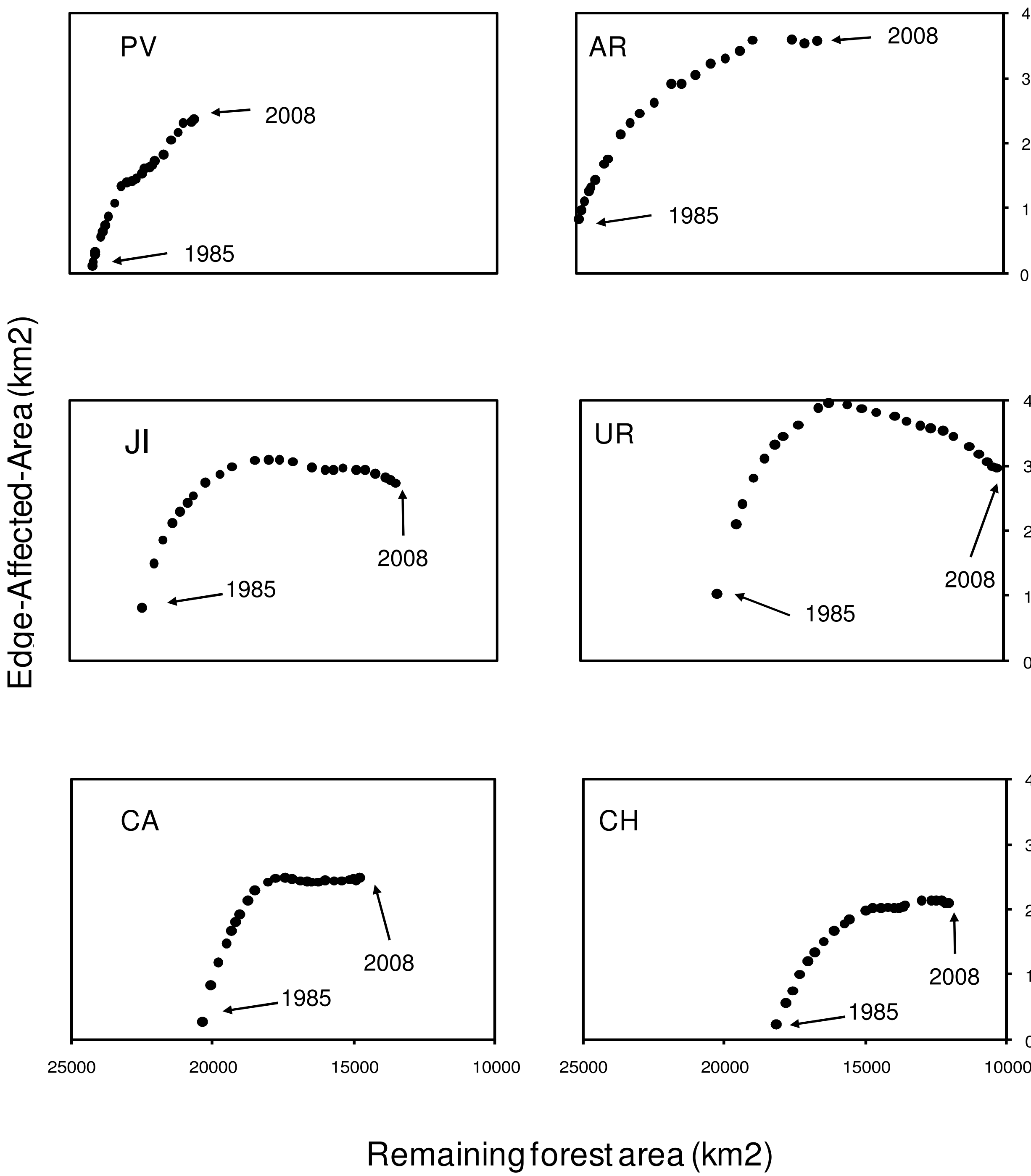

Figure 4. Changes in edge-affected forest areas as a function of remaining forests for the six Landsat scenes (identified in Figure 1 caption). Each dot refers to a year of the study period (1985–2008, left to right).

[16] To evaluate the impact of edge age on biomass loss and carbon and not considering any other sources of forest degradation such as fire, the forest edge ages were divided into three age classes, 1–4, 5–13, and >13 years old. The 1–4 edge age class accounts for the period of active biomass collapse. The 5–13 year old edge age class captures the period of continued carbon loss due to decomposition following biomass collapse. The class >13 year old includes edges that are no longer emitting carbon. To evaluate dynamics of biomass loss and carbon emissions through time, biomass loss and carbon emissions from each class were calculated for two different years: 1998, 14 years after the start of deforestation, covering the minimum time period for the whole process of biomass collapse and carbon

Table 1. Summary of Biomass Loss and Carbon Emission From Deforestation and Edge Effects for the Study Scenes Between 1985 and 2008

Year	Deforestation Biomass Loss (Tg)	Edge Biomass Loss (Tg)	Total Biomass Loss (Tg)	Deforestation Carbon Emissions (Tg)	Edge Carbon Emissions (Tg)	Total Carbon Emissions (Tg)
1985	21.48	1.60	23.08	2.99	0.08	3.07
2008	23.31	2.34	25.65	19.89	0.95	20.84
Total	922.73	84.12	1006.85	425.46	24.93	450.40
Average	38.44	3.51	41.95	17.73	1.04	18.84

emissions to occur; and 2008, 24 years after the start of deforestation including additional 10 years of dynamics. The evolution of the process will be evaluated by comparing the two different time periods.

4. Results

4.1. Dynamics of Deforestation and Edge-Affected Forest

[17] Total deforestation over the six scenes between 1985 and 2008, increased by 42,787 km^2, equivalent to 33% of the total forested area in 1985, representing an average deforestation rate of 1.9% or 1860 km^2 yr^{-1} (Figure 3a). Edge-affected forest areas, the area of intact forest contained in edges subject to biomass collapse, increased from 2714 km^2 in 1985 to 16,145 km^2 in 2008 (Figure 3b). Edge-affected forest areas increased dramatically at the early stages of deforestation then began to roughly stabilize even with expansion of deforestation. As ongoing deforestation continues, new forest edges are added and older edges are eliminated, 13% of edge-affected forests were lost annually in our study region. Different temporal patterns of edge-affected forest areas were observed according to the stages of deforestation across the study scenes (Figure 4). Between 1985 and 2008, a decrease of edge-affected forest areas was observed together with a decrease in remaining forest area in advanced deforestation regions such as JI and UR. In contrast, new frontier regions such as PV and AR showed an increase in edge-affected forest areas throughout the study period. Similar landscape patterns, related to deforestation stages, have been observed in previous studies [*Laurance et al.*, 1998; *Cochrane and Laurance*, 2002; *Numata et al.*, 2009].

4.2. Edge-Induced Biomass Loss and Carbon Emissions

[18] During the period between 1985 and 2008, 923 Tg of live aboveground biomass (38 Tg yr^{-1}) in the study region was lost due to deforestation (Table 1). Over the same time period, biomass loss from forest fragmentation was calculated at 84 Tg, 3.5 Tg yr^{-1}. Edge-induced biomass accounted for 8.4% of the total biomass lost (1007 Tg). As of 2008, collapsed biomass was equivalent to 0.1% of total aboveground biomass of remaining forest. In the case of carbon, edge–derived carbon emissions were 0.08 TgC in 1985 and 0.95 TgC in 2008 against 2.99 and 19.84 TgC from deforestation in the same years. On average, 1.04 Tg of carbon was released from forest edges annually, which is equivalent to 5.9% of deforestation-derived carbon (17.73 Tg) or 5.5% of total carbon emissions (18.84 Tg) (Table 1).

[19] The dynamics of edge-induced biomass loss and carbon emissions varied spatially and temporally. The spatial distribution of biomass loss and edge carbon flux across Rondônia changed following the process of deforestation (Figure 5a). In 1988, a high degree of biomass loss was observed in the central region (Figure 5b), with 1.38 and 1.44 Tg in JI and UR, respectively; losses were concentrated along the main roads such as the highway BR364 and the adjacent roads. Following 1988, new deforestation frontiers begin to expand. In 2008, a high-edge biomass loss was observed in the new development region around Buriti county in the AR scene (the northwest of the region), reaching nearly 1.0Tg, whereas older colonization regions along BR 364 such as JI and UR showed reduced biomass loss at 0.35 and 0.25 Tg, respectively, primarily due to presence of extensively fragmented small forest areas. The amount of biomass loss due to edge effects reached the peak in 1988, 4 years after the start year, 1985, then begun to decrease (Figure 6a). Since the process of biomass collapse lasts only 4 years after forest fragmentation, even though the area of edge-affected forest expands each year, areas older than 4 years old do not add any new collapsed biomass.

[20] Carbon emissions from forest edge showed similar trend to biomass loss (Figure 5c), but temporal changes of carbon were less drastic, since the process of carbon emissions requires 13 years to reach completion, compared to 4 years for biomass collapse (Figure 6b). The peak of carbon emissions from edges in our study area was in 1996. Over the entire study region, carbon emissions from deforestation continued to increase until 2006 (Figure 7a), whereas the remaining forest continued to decrease linearly (Figure 3). Edge-affected forests added extra carbon to carbon derived from deforestation annually varying from 2.6% to 10% (Figure 7a). The JI scene, an old colonization region, showed a decrease of carbon release from both deforestation and forest edges (Figure 7b), whereas carbon emissions of deforestation and edges in AR continue to grow up to 2008.

[21] The impact of changes in the composition of edge age on biomass loss and carbon emissions is shown in Table 2. Although edge-affected forest areas were similar between 1998 and 2008, the composition of their forest edge ages differed. In 1998, 14 years after the start of deforestation of the study period, 1–4 year old (an active period for biomass loss) and 5–13 year old edge age classes (the carbon emission period) occupied 95% of total edges, decreasing to 62% by 2008. By contrast, the >13 year old edge age class (no carbon emission period) increased from 5% in 1998 to 38% in 2008. The shift of edge ages from young to old in the 1998–2008 period resulted in the reduction of biomass loss by 33% and of carbon emissions by 22%–33%. This result indicates that younger landscapes will have larger

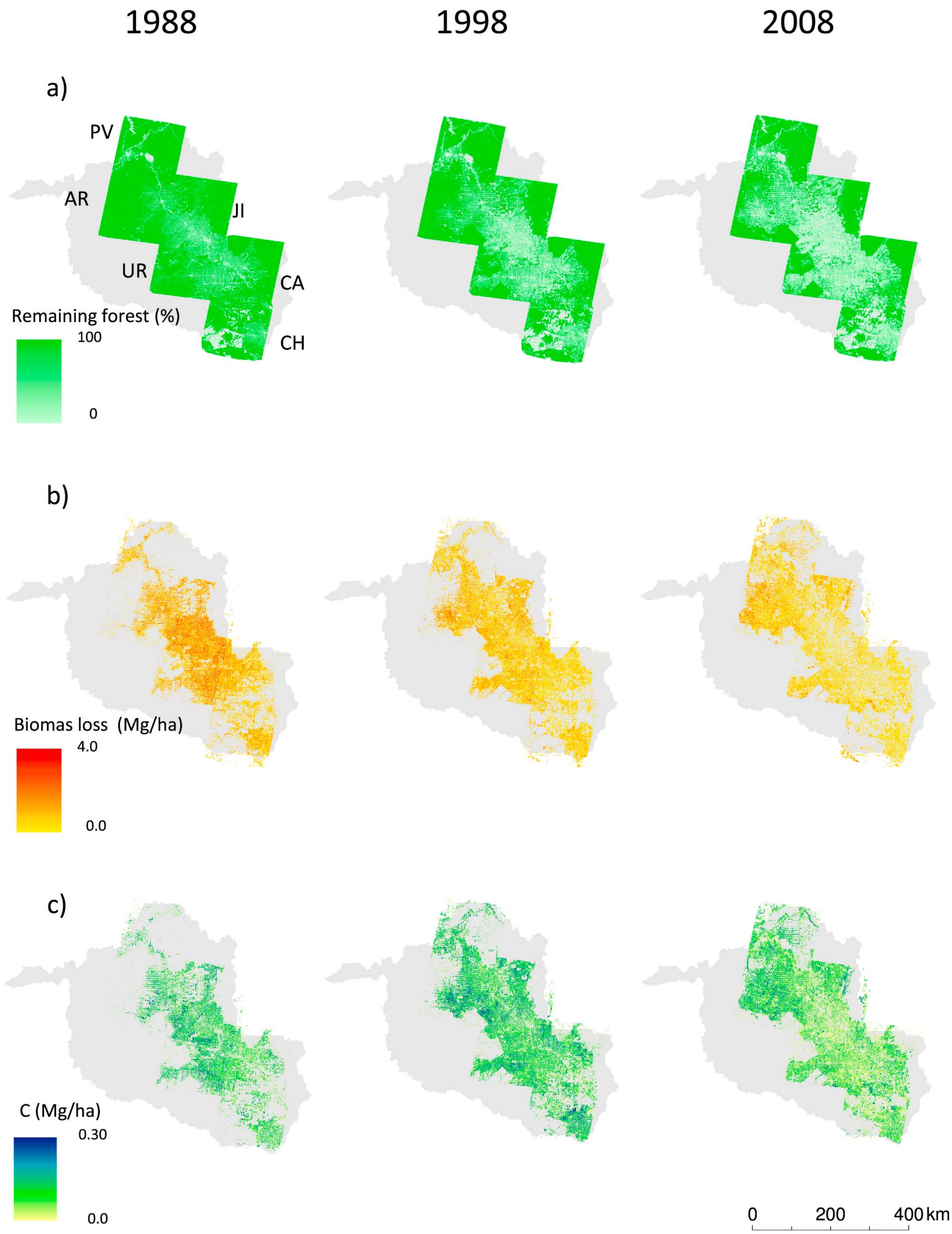

Figure 5. Dynamics of (a) remaining forests, (b) edge biomass loss, and (c) edge carbon emission in 1988, 1998, and 2008.

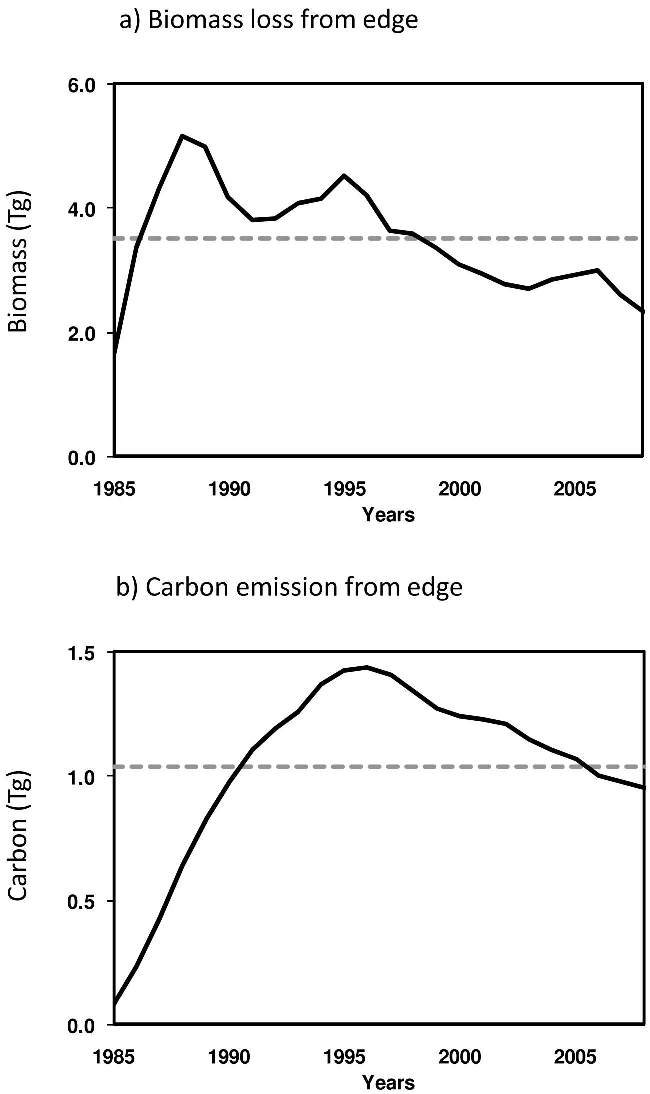

Figure 6. Temporal changes of (a) biomass loss and (b) carbon emission. Solid lines are year-to-year measures of biomass loss and edge carbon emissions, and gray dashed lines refer to the mean values across the study period.

edge-derived biomass losses and carbon emissions than older landscapes.

[22] When estimating edge-related carbon emissions, it is important to keep track of the erosion of forest edges over time. Although we estimate that a total of 24.94 TgC was emitted by edge-related processes (6% of those from deforestation), this does not mean that all of this carbon is unaccounted for in deforestation-based carbon emissions estimates. For example, as of 2008, we estimate that between 1985 and 2008, all of the remaining and new edges in 2008 had released 15.75 TgC (0.95 TgC emitted in 2008 and 14.80 TgC emitted before 2008), approximately 3.6% of the emissions estimated from deforestation alone during the same period, 435.60 TgC, i.e., total carbon emission during the 1985–2008 period (450.40 TgC), edge-related carbon emitted before 2008 (14.80 TgC). This is the amount of edge-related carbon that would not have been accounted for by deforestation-based estimates alone.

5. Discussion

5.1. Where and When Do Biomass Loss and Carbon Emissions From Forest Fragmentation Become Critical?

[23] Our results showed the dynamics of edge-induced biomass loss and carbon emissions across space and time. The dynamics change as a function of deforestation rates

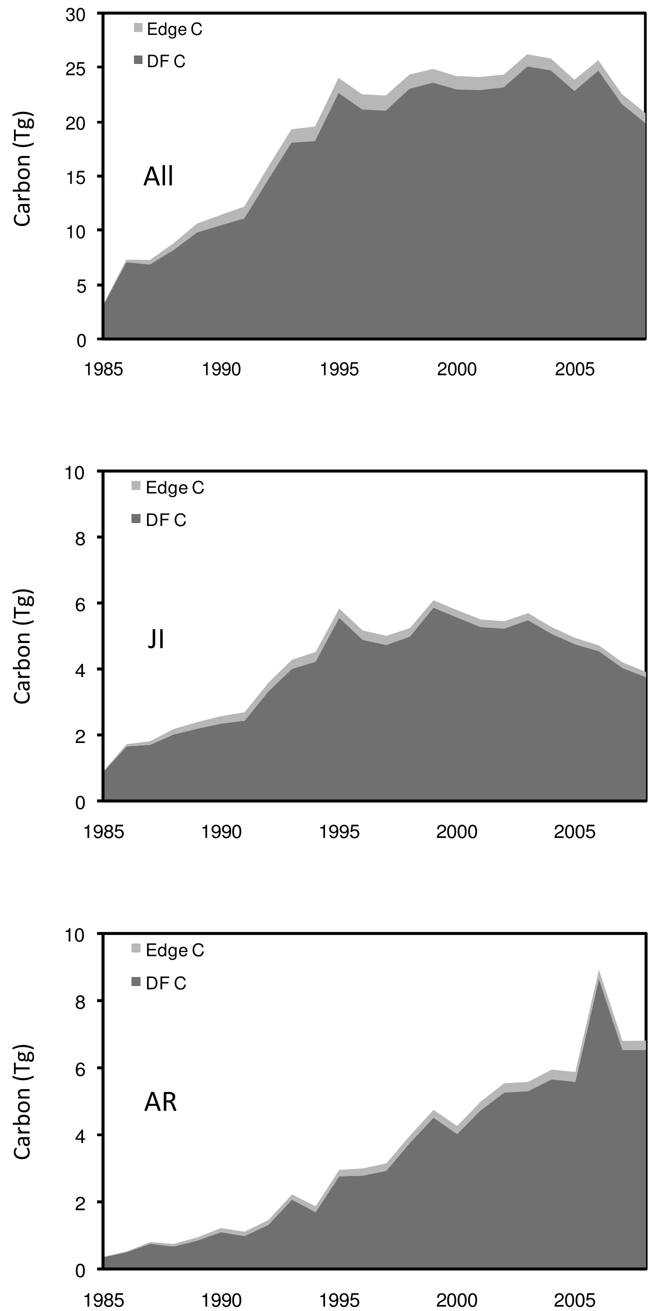

Figure 7. Temporal changes of carbon emissions from deforestation and edges for the entire area, JI, and AR scenes.

Table 2. Effects of the Composition of Edge Ages on Biomass Loss and Carbon Emissions

Edge-Affected Forests	1998 15,344 km^2	2008 16,145 km^2
1–4 years old	37.61%	23.50%
5–13 years old	57.44%	38.42%
>13 years old	4.95 %	38.08%
Edge biomass loss	3.59 Tg	2.34 Tg
Edge carbon	1.34 Tg	0.95 Tg

and extent of edge-affected forest [*Laurance et al.*, 1998], but the composition of edge ages of these areas is an important factor, since biomass loss and carbon release due to edge effects will vary as a deforested landscape ages. *Numata et al.* [2009] found that the persistence of forest edges is very short, with 50% of forest edges eliminated in less than 5 years and 80% eliminated in 10 years following forest fragmentation. Therefore, many edge-affected forests may not complete the process of biomass collapse and associated carbon emission limiting their effect. On the other hand, the composition of edge ages changes across the landscapes at different stages of deforestation [*Numata et al.*, 2009]. Active deforestation regions along the frontier will tend to add new edges more rapidly than the older edges are eliminated and thus will include a greater percentage of edges in the active process of biomass collapse and subsequent carbon emissions. Consequently, large contributions to annual biomass loss and edge-related carbon emissions are expected from these active deforestation regions with young edges. Advanced and older deforestation regions are dominated by older edges (Table 2), resulting in a lower annual loss of biomass and emission of carbon from edges.

[24] Spatial arrangements and geometries of forest fragments are also an important factor modifying edge-biomass loss and carbon emission. *Laurance et al.* [1998], in their simulation study, found that a landscape with settlement deforestation pattern of small farms/settlement (fishbone pattern) as occurred in Rondônia, produced 5 times more edge carbon emissions than a landscape with a clearing pattern of large cattle ranches, such as occurs in Pará. In our study, most of our study scenes consisted of small farms or settlements or were dominated by small farms with some larger cattle ranches. For example, CH, which contained both clearing patterns (i.e., large cattle ranches and settlements), also had lowest carbon emissions compared to the other scenes. However, this region, which is in the transition zone with Cerrado, also consisted of lower biomass classes. Furthermore, this region was the most extensively deforested before 1984. Recent conversion of vast forested area into soy plantation in Mato Grosso [*Morton et al.*, 2006] or other large cattle ranch-driven deforestation may result in regional differences of edge carbon contributions due to land use patterns. Regional analysis of biomass collapse and carbon emissions from edges in terms of different land cover and land use patterns will be necessary in the future.

5.2. Sources of Uncertainty

[25] The analysis was performed starting in 1985 due to the lack of land -cover-change history prior to this time, even though deforestation had begun much earlier and a considerable area had already been deforested, especially along roads in JI, UR, and CA. Therefore, the deforestation rates of these regions were already very high with large edge-affected forest areas present in the 1–4 year class. Thus our approach does not account for earlier edge-affected losses in these areas. The start year for the analysis should have influenced the patterns of biomass loss and carbon emissions, since carbon fluxes are tightly related to the historical land cover changes [*Ramankutty et al.*, 2007]. The temporal pattern of edge biomass loss and carbon emissions of these regions, like JI, might be much smoother with gradual increases through time if the dynamics could be followed since the beginning of deforestation. AR, where major deforestation started after 1985, probably shows a representative temporal pattern of biomass loss and carbon emissions in the early stage of the process.

[26] In terms of the quality of the land cover change maps, from which the age map was generated, overall accuracy of the annual land cover maps is 85.4% for six different land cover classes. However, the accuracies for the classes "primary forest," "nonforest," and "water" is 93.8% [*Roberts et al.*, 2002]. We did not quantify the impact of the accuracies of our land cover maps on the estimate of carbon emissions from deforestation and edges. Since the age map was created based upon the dynamics of forest and nonforest areas through time and did not consider other land cover types that are prone to classification error (e.g., second growth), the accuracy of the land cover data would not be a substantial source of uncertainties and its implication for this study would be small.

[27] The rates, effective edge distance, and period of biomass collapse used in this study were from a single landscape (Manaus) in the Amazon published by *Laurance et al.* [1997]. Although the biomass collapse and other edge effects on remaining forests have been well documented in this landscape, the variability of these parameters across the Amazon region is highly uncertain. In our study, we assumed the event of biomass collapse within 100 m forest edges during the first 4 years only, whereas biomass collapse occurs up to 300 m of edge in a longer period (6–9 years) [*Laurance et al.*, 1997]. Therefore, our results may be conservative. On the other hand, edge effects on remaining forests may be much less significant in other tropical regions due to favorable environmental conditions such as fertile soil types [*Phillips et al.*, 2006]. Another key uncertainty is the decomposition rate of dead biomass. Although decomposition of dead biomass likely occurs faster in forest edges than in forest interiors [*Nascimento and Laurance*, 2004], the temporal pattern of decomposition rates is not well understood. For more accurate estimates of biomass collapse and carbon emissions from forest edges, the effects of adjacent land use types, such as pasture and crops on biomass collapse need to be investigated.

6. Conclusions and Implications

[28] Despite the uncertainties mentioned above, our study showed potential spatial and temporal patterns of biomass loss and carbon emissions from edges according to actual dynamic fragmented landscapes in Rondônia, identified using a time series satellite data set. According to our models, forest fragmentation accounted for 9.1% of the total biomass loss and was responsible for approximately 6% of

the average net annual carbon release between 1985 and 2008 in Rondônia. The unaccounted carbon emissions are reduced to 3.6% of those that would be estimated from deforestation alone, however, once edges deforested during the study period are taken into account. These amounts are as high as the estimated carbon emissions due to selective logging, i.e., 4%–7% of the release from deforestation [*Nepstad et al.*, 1999]. Many deforestation-related carbon estimate models for tropical regions have adopted, within the total carbon emissions, the amount of 4%–7% as the net carbon release due to forest degradation [e.g., *Houghton et al.*, 2000; *DeFries et al.*, 2002]. However, with the addition of potential carbon emissions from forest fragmentation, carbon fluxes from degraded forests may exceed 10%. Furthermore, since selective logging and forest fragmentation sharply elevate fire risk by increasing forest desiccation and fuel loads, synergic interactions between fires, fragmentation, and logging may substantially increase the effects of the biomass collapse, causing much larger fluxes of carbon to the atmosphere [*Cochrane*, 2001, 2003; *Cochrane and Laurance*, 2008]. The results of this study can improve our knowledge about edge effects on regional carbon fluxes and contribute to reducing the uncertainty about the magnitude of carbon emissions from forest degradation, which is the key component for those global carbon dynamic research projects such as Reducing Emissions from Deforestation in Developing Countries.

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