The impact of selective logging on carbon storage and fluxes over Brazilian Amazon

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1. Motivation and background

Monitoring selective logging from space

Tropical forests have been threatened by increasing rates of forest degradation during the past three decades. Although deforestation, largely for the conversion of land to food crops or pastures, is the major destructive force in tropical forests worldwide (Houghton et al., 2000), other forest disturbances such as the selective harvest of timber have also increased in frequency and extent (Nepstad, et al., 1999). In selective logging, a limited number of marketable tree species are cut, and logs are transported off site to sawmills. Unlike deforestation, which is readily observed from satellites, selective logging in the Brazilian Amazon causes a spatially diffuse thinning of large trees, which is hard to monitor using satellite observations. Selective logging causes widespread collateral damage to remaining trees, sub-canopy vegetation, and soils, with impacts on hydrological processes, soil erosion, fire, carbon storage, and plant and animal species.

Recent remote sensing studies have made the monitoring of selective logging possible from the space. Asner et al. (2005a, 2005b) developed a large-scale, high-resolution, automated remote-sensing analysis of selective logging and applied it to the top five timber-producing states of the Brazilian Amazon. Their results show that logging rates ranged from 12,075 to 19,823 km^2 per year (±14%) between 1999 and 2002 in these states, equivalent to 60-123% of previously reported deforestation (forest clear-cut) area for those years.

CASA-3D: an ecosystem model for tropical forest disturbance and selective logging

To understand the impact of selective logging on the regional carbon budget, an ecosystem modeling approach is desired. Unfortunately, current ecosystem models either operate at a broad spatial scale incompatible with diffuse forest disturbances such as selective logging, or at a very fine spatial scale that cannot easily ingest high-resolution data on forest canopy damage and disturbance over large geographic regions. The Ecosystem Demography (ED) model is an exception in that it is an individual-based terrestrial biosphere model which can be scaled to large areas (Moorcroft et al., 2001). However, it lacks an ability to simulate the carbon budget following disturbance such as selective logging. In the case of selective logging, an appropriate modeling approach is needed to simulate timber harvest impacts over large regions, meanwhile properly accounting for a necessary lack of site-specific information that is not expressed in remote sensing data (e.g., changes in forest community composition, light conditions, and stand structure after disturbance).

To address these issues, Huang et al. (2008) developed a new version of the Carnegie-Ames-Stanford Approach (CASA) ecosystem model (CASA-3D) designed specifically to quantify changes in carbon storage and fluxes following forest disturbance in humid tropical forests. The major new features of CASA-3D include: (1) an alternative way of estimating absorbed photosynthetically-active radiation (APAR) by taking advantage of new high-resolution satellite maps of forest canopy gap fraction (Asner et al. 2005b); (2) a pulse disturbance module to realistically modify carbon pools after forest disturbance; (3) a regrowth module that addresses changes in community composition following disturbance with a new set of parameterizations based on field observations of gap-phase regeneration; and (4) a radiative transfer module for charactering the dynamic three-dimensional light environment above the canopy and within gaps after disturbance. The model was calibrated with and tested against field observations from experimental logging plots in the Large-scale Biosphere Atmosphere Experiment in Amazonia (LBA) project, and the sensitivity of key model parameters were evaluated with Monte Carlo simulations.

In this study, CASA-3D was applied to the states of Para and Mato Grosso in Brazilian Amazon to assess the pre- and post-logging carbon storage and fluxes over the region.

2. Data and methodology

Meteorological data: the South America Meteorological Data Set from 2000 to 2004 at a 40×40 km^2 resolution, developed by the Center for Weather Forecasts and Climate Studies (CPTEC) of the National Institute for Space Research (INPE), Brazil. Mean annual cycles of temperature, precipitation, and solar radiation over these five years were used.

Soil texture map: NASA Ames Research Center Amazon Ecology (AME) Mapping Data Sets (Potter et al., 1998) at an 8×8 km^2 resolution

Logging images: the gap fraction images from 1999 to 2002 over Para and Mato Grosso (Asner et al. 2005b) at a 28.5*28.5 resolution

A statistical modeling approach:

Applying an ecosystem model to a region as large as Amazon at a spatial resolution of 28.5*28.5 m^2 is not trivial, even with the computational capacity of a cluster. Therefore, in this study, we adapted a statistical approach to realize the simulations.

- **Spin-up**

we resized the meteorological data into a 8×8 km^2 grid. For each of the 8×8 km^2 cells, we assumed that the pre-logging gap fraction (range from 0-1.0) of the 28.5*28.5 m^2 pixels within it would take one of the following values on its histogram: 0, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.6, 0.7, 0.8, 0.9, 1.0. CASA-3D was then initialized with each of the 24 values of gap fraction by repeatedly feeding the mean monthly meteorological data into the model for 500 years, to generate a steady state for all carbon pools. The 24 sets of spin-up carbon pools were mapped back to the 28.5*28.5 m^2 resolution based on the gap fraction map in 1999 (i.e., the year before all the logging events occurred) to generate a carbon storage map over Para and Mato Grosso.

- **Simulations**

15 damage levels were assumed: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.60, 0.70, 0.80, 0.90, 1.0, where damage level is defined as the change in gap fraction before and after logging. Asner et al. (2005a) showed that the average gap fraction of pre-logging forests in Amazon is around 0.07. Therefore, we carried out the post-logging simulations by assuming the pre-logging gap fraction to be 0, 0.05, 0.10, respectively. For each of these assumed pre-logging gap fraction values, CASA-3D was applied to simulate dynamic regrowth of the forest in 100 years following selective logging with different assumed damage levels at an 8×8 km^2 resolution. These results were mapped back to the 28.5*28.5 m^2 resolution based on the gap fraction images and damage images in Asner et al. (2005b) to generate maps of forest recovery over the logged regions.

3. Results

Table 1. Statistics of carbon storage before logging over Mato Grosso and Para*

Carbon (Mg C/ha)	Mato Grosso and Para(n=31019) Mean	Max	Std
Foliage	5.1	8.5	2.5
Wood	116.4	193.3	56.42
Fine Roots	5.1	8.5	2.5
****Soil Organic Carbon**	19.9	41.9	9.7
*****Coarse Woody Debris**	20.9	52.8	10.8

* Statistics were obtained based on the aggregated 8×8 km^2 map
** Soil organic carbon includes surface and soil microbial, structural, slow and passive pools (see Parton et al. 1989).
** *Coarse woody debris includes fine, medium and coarse fractions as described by Huang et al. (2008)

Table 2. Impact of selective logging on regional carbon budget (aggregated*)

	Before logging	Difference between pre-logging and post-logging values**					
		1yr	5yr	10yr	20yr	30yr	40yr
Annual NPP (Tg C/yr)	58.23	-15.38	-8.86	-7.14	-3.12	-1.75	0.01
Annual RESP (Tg C/yr)	58.34	24.43	2.81	0.22	-2.09	-2.93	-2.71
Live C (Tg C)	972.95	-304.61	-284.79	-265.99	-231.54	-197.20	- -
CWD (Tg C)	176.68	234.77	120.55	59.61	-1.47	-21.83	- -
Soil C (Tg C)	180.32	26.07	26.87	32.18	21.53	9.94	- -

- Based on all the 28.5×28.5 m^2 pixels identified as logged in Asner et al. 2005b, total logged area: 53225 km^2

** positive and negative signs indicate increase (gain) and decrease (loss), respectively.

Table 3. Impact of selective logging on regional carbon budget (averaged*)

	Before logging	After logging 1yr	5yr	10yr	20yr	30yr	40yr
Annual NPP (Mg C/ha/yr)	11.07 (10.98)*	8.15 (4.82)	9.38 (5.43)	9.71 (5.61)	10.48 (6.05)	10.74 (6.20)	11.07 (6.39)
Annual RESP (Mg C/ha/yr)	11.09 (10.96)	8.15 (9.30)	15.73 (6.66)	11.62 (6.39)	10.69 (6.16)	10.74 (6.07)	10.58 (6.08)
Live C (Mg C/ha)	184.95 (106.92)	127.04 (77.98)	130.81 (80.03)	134.38 (80.74)	140.94 (83.49)	147.46 (86.40)	- -
CWD (Mg C/ha)	33.59 (20.50)	78.21 (51.50)	56.50 (36.66)	44.92 (28.23)	33.31 (20.55)	29.44 (18.12)	- -
Soil C (Mg C/ha)	34.28 (20.87)	39.23 (24.30)	39.38 (24.23)	40.39 (24.69)	38.37 (23.56)	36.37 (22.23)	- -

- Values shown are mean and standard deviations
  Based on all the 28.5×28.5m^2 pixels identified as logged in Asner et al. 2005b, n=10114

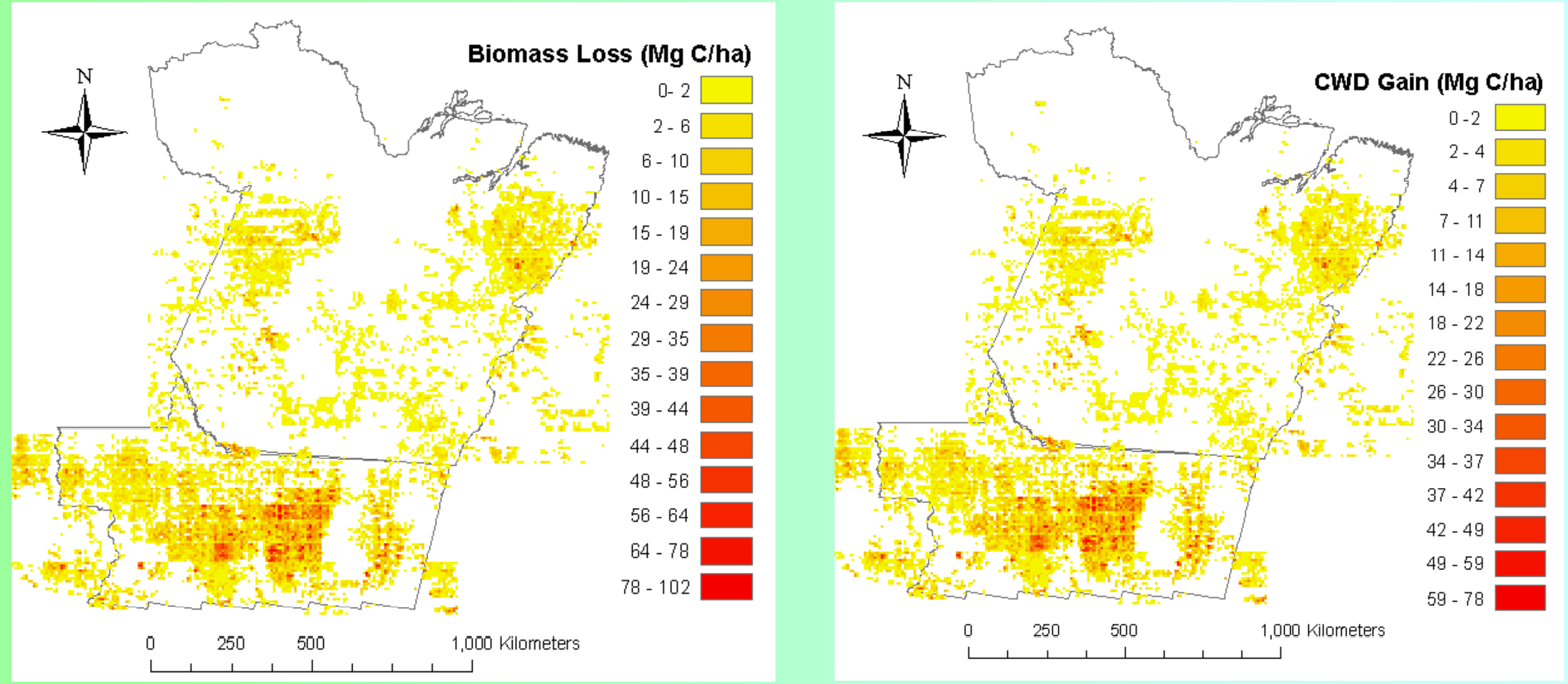

Figure 1. Spatial distribution of (1) total living biomass lost and (2) increase in coarse woody debris due to logging in years 2000-2002 over Para and Mato Grosso at an 8×8 km^2 resolution.

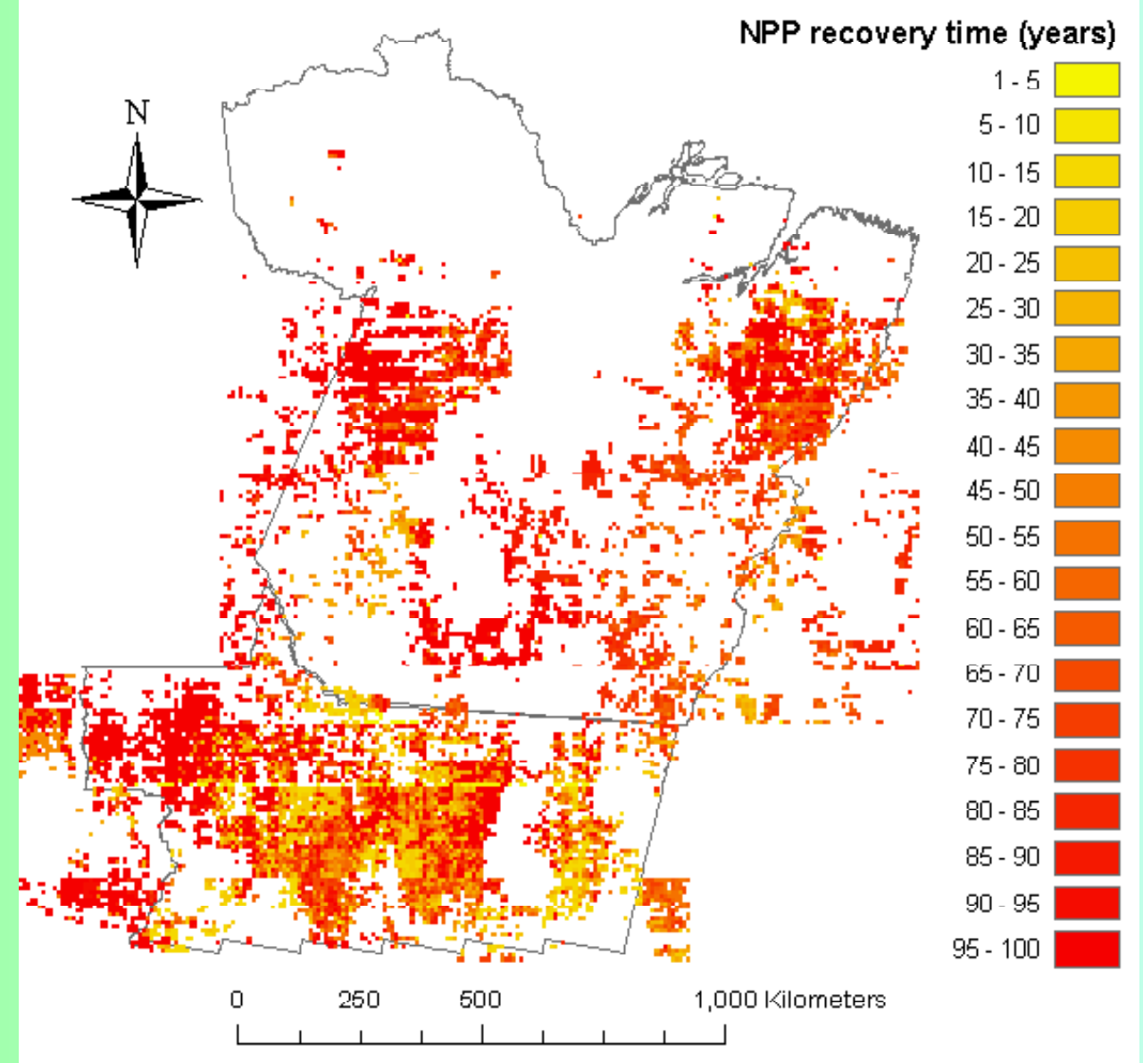

Figure 2 Spatial distribution of the recovery time (in years) for NPP to reach its pre-logging level

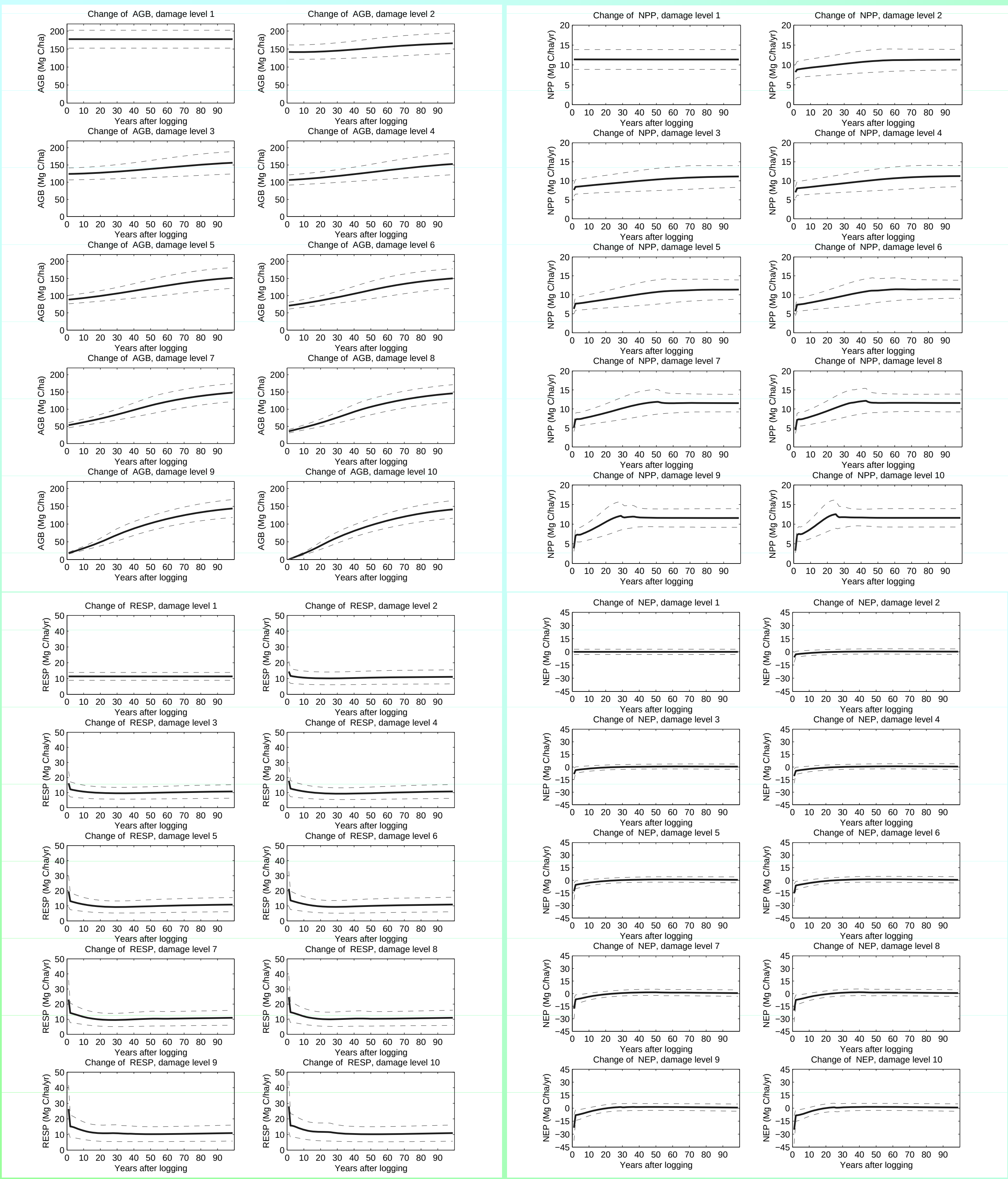

Figure 4. Change of (a) AGB, (b) NPP, (c) RESP, and (d) NEP over Para and Mato Grosso in pixels with different logging intensities. Damage levels 1-10 correspond to gap fraction change of 0.05 (no logging), 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, respectively.

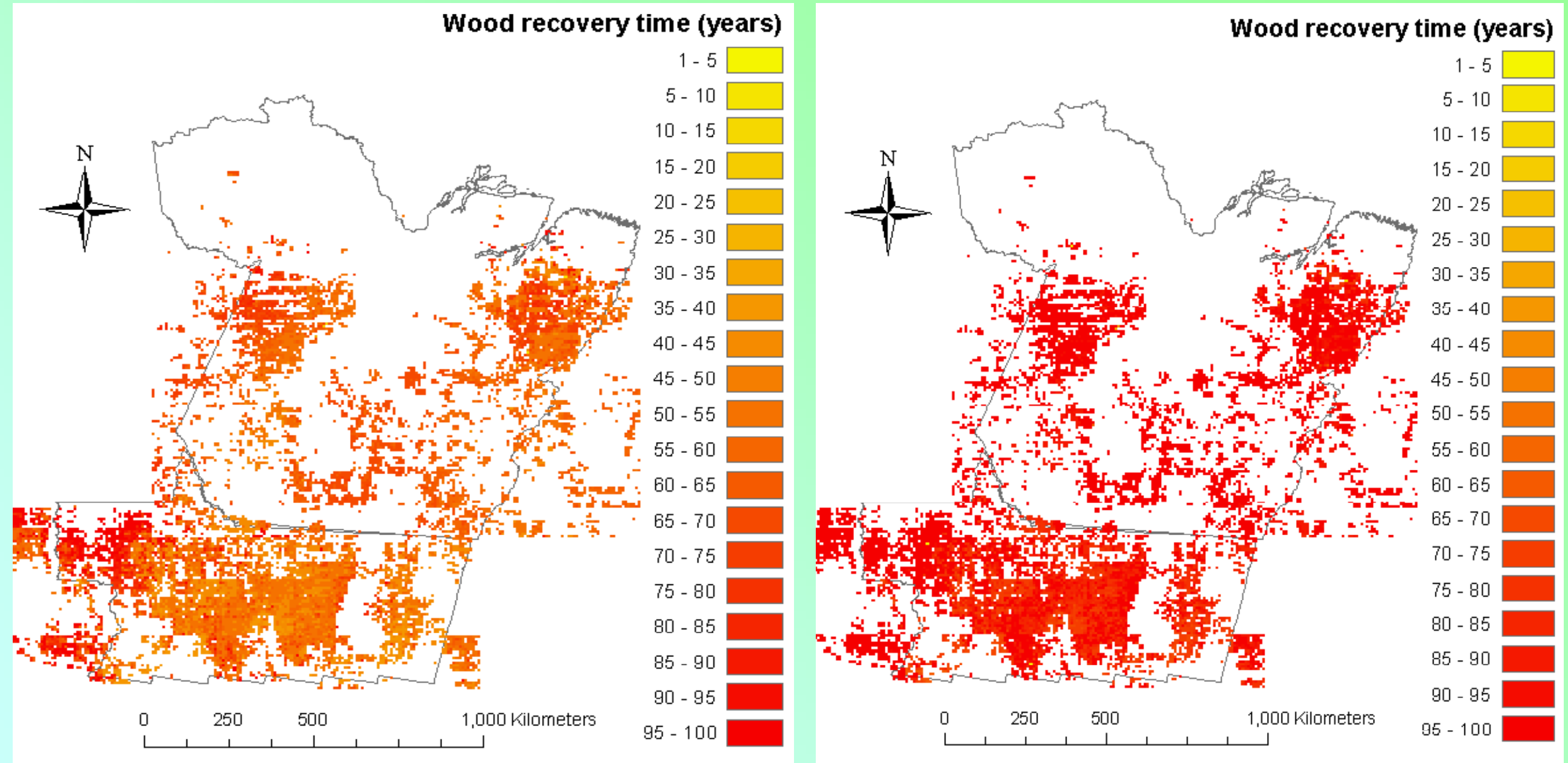

Figure 3. Spatial distribution of time (in years) for the wood C pool to recover (a) 50% and (b) 75% of its logged portion.

4. Conclusions

Our results confirm that by changing forest architecture and composition, selective logging result in a cascading set of impacts on the carbon cycling of rainforest ecosystems. Specifically,

- Logging initially suppresses NPP of the ecosystem by removing a large fraction of foliage. Because it is hard for light to penetrate into the logging-generated gaps due to the 3-D shadowing of trees around the gaps, NPP recovers slowly afterwards, even at the lowest logging intensity. Consequently, basinwide, the average recovery time for NPP to reach its pre-logging level is 72 years, and the average time for the wood C pool to recover 50% and 75% of its logged portion are 62 and 94 years, respectively.

- A significant amount of damaged biomass, including leaves, wood, and roots, enters the detrital pools, which increases the ecosystem heterotrophic respiration for years following timber harvest. The total biomass lost due to logging activities in 2000-2002 accumulated to be 304.61 Tg C over Para and Mato Grosso, which results in a 234.77 Tg C increase in CWD pools.

- Selective logging turns the Amazon forest system to a huge source of carbon to the atmosphere in three decades after logging. The net carbon source in the first year following logging alone is as high as 40 Tg C. Afterwards, the system becomes a slight carbon sink to guarantee the recovery of the damage areas