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Tropical forest degradation in the Brazilian Amazon – relation to fire and land-use change

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Abstract
While deforestation represents an obvious ecosystem change, forest degradation is often more difficult to discern or quantify, but it impacts a number of ecosystem functions which are vital for biodiversity and climate feedbacks. In the Brazilian Amazon, land-use changes increase fire occurrence, especially in fragmented forests close to managed land. We used remote sensing imagery to estimate the extent and impact of forest fires in degraded tropical rain-forest in the Brazilian Legal Amazon between 2007 and 2010 and examined land-use establishing in degraded areas. The trends in degraded area vs. burned area were different. Even though degradation increased one year after a high fire year, there was no spatial overlap, which points to other causes for degradation. Up to 11% of the degraded area was burned in the same year, playing escaping fires from managed and deforested lands a significant role in degradation by fire. Eighty-four percent of 2007s degraded area remained forest one year later, whereas the rest was identified as deforestation, secondary vegetation or pasture. Three years after degradation, 80% remained forest, the proportion of deforested area decreased and areas in regeneration after being deforested increased. Monitoring of forest degradation across tropical forests is critical for developing land management policies and for carbon stocks/emissions estimation.

Keywords: *forest degradation, logging, forest fires, land-use, Brazilian Amazon.*

1. Introduction

In Brazilian Amazonia, the extent of canopy and subcanopy disturbance has been underestimated and often exceeds the total area deforested (Peres *et al.*, 2006; Souza Jr. *et al.*, 2013). Deforestation in the region is superimposed upon synergistic processes of anthropogenic forest degradation (events when, unlike in deforestation processes, the forest canopy cover is only partially or temporarily removed), which implies the reduction in the overall capacity of a forest to supply goods and services (Simula, 2009). Several aspects of the forest may be affected by degradation including productive capacity, protective capacity, biodiversity and health and carbon storage (Parrotta *et al.*, 2012). The proximate drivers of forest degradation include unsustainable and illegal logging, human-induced fires, over-harvest of fuelwood and non-timber forest products, overgrazing and poor management of shifting cultivation (Chazdon, 2008; Kissinger *et al.*, 2012). In addition to these adverse impacts of land-use change and human-induced forest degradation, climate change poses an increasing threat to tropical forest ecosystems increasing the frequency of severe droughts (Malhi, 2012).
In the Brazilian Amazon humans have substantially altered forest fire regimes and fires have increased in extent and frequency as a result of forest fragmentation, the expansion of managed lands and logging (Asner *et al.*, 2005; Morton *et al.*, 2008; Armenteras *et al.*, 2012), thus contributing to forest degradation and reducing forest resilience (Barlow and Peres, 2008; Nepstad *et al.*, 2008). Moreover, forest fire can increase susceptibility to further burning in a positive feedback by killing trees, opening the canopy and

increasing solar penetration to the forest floor (Cochrane and Laurance, 2008; Alencar *et al.*, 2011). Anthropogenic forest disturbance from fires produces long lasting changes in forest structure and biomass but the changes are sometimes hard to detect in satellite imagery and are quickly obscured by the regenerating forest canopy (Matricardi *et al.*, 2010), which makes it difficult to properly assess forest degradation by fire.

In 2007, at its 13th Conference of the Parties, the UN Framework Convention on Climate Change recognized forest degradation as an important contributor to global carbon emissions by incorporating it into the Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism (UNFCCC, 2008). According to van der Werf *et al.* (2010), the global sum of deforestation, degradation, and peat fire emissions accounted for about a quarter of total carbon emissions. Another study by Asner *et al.* (2005) estimated that emissions caused only by selective logging were equivalent to between 60 and 123% of previously reported deforestation emissions in five states of the Brazilian Amazon, which accounted for 90% of all deforestation in the region, while Pearson *et al.* (2014) found that Brazil's emissions from logging were small and equivalent to 10% of those from deforestation. Nevertheless, the release of carbon by degradation still remains largely overlooked, and limited information is available to achieve a full carbon accounting for REDD+ (Morton *et al.*, 2011a). The scientific, conservation, and climate policy importance attracted previous studies to analyse forest degradation processes in the Brazilian Amazon through field research (Xaud *et al.*, 2013; Berenguer *et al.*, 2014) and remote sensing observations (Matricardi *et al.*, 2010; Souza Jr. *et al.*, 2013). Further progress, however, is yet to be made in quantifying the extent and intensity of less-visible forms of nonstructural habitat disturbance underneath the forest canopy. In this line, our study pursues the quantification of the degraded area affected by fires in the Brazilian Amazon and also their temporal changes using 30x30 m land-cover information (INPE and EMBRAPA, 2013). Specifically, we answer three main questions. 1) What is the relation between forest degradation and fire? 2) To what extent do fires escaping from managed land contribute to forest degradation? 3) What are the temporal dynamics of degraded areas and their conversion to other land-use types?

2. Methods

2.1. Study area

The Brazilian Amazon contains about 3.2 million square kilometers of the Amazon forest (INPE and EMBRAPA, 2013) and stores the majority of the 126 Pg of carbon reported for the entire Amazonia (Malhi *et al.*, 2006). About 80% of the forest remains intact (FAO-ITTO, 2011), although substantial areas have been deforested (INPE, 2013a), selectively logged (Asner *et al.*, 2005; Matricardi *et al.*, 2010) or affected by fires in recent decades (Morton, 2013; Xaud *et al.*, 2013). As a consequence of that rapid land-cover change, the forest has been fragmented by logging gaps and mosaics of cattle ranching and agricultural settlements, mainly along the arc of deforestation in southern and eastern Brazilian Amazon (Houghton *et al.*, 1991; Lambin *et al.*, 2003; Lepers *et al.*, 2005). In this paper we use the Brazilian Legal Amazon definition, the largest Brazilian socio-geographic division (Figure 1), which, in 2010, was covered by primary or secondary forest (76%), savanna-type vegetation (18%), concentrated mainly in the southeast, and 6% was detected as cleared areas (Figure 1a).

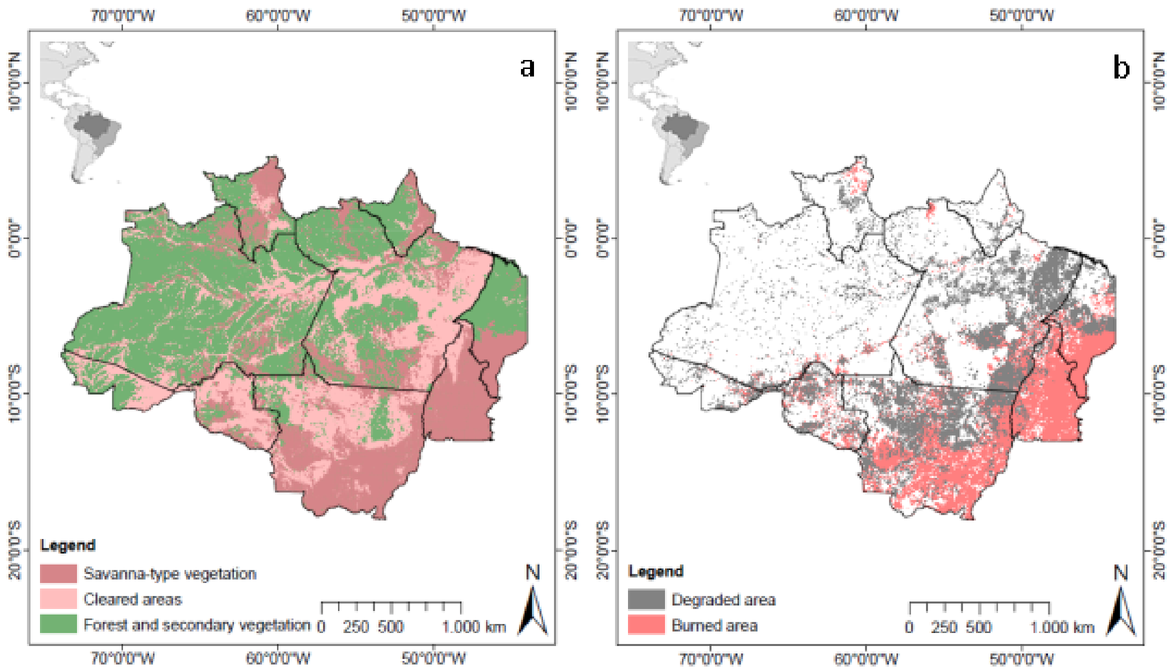

Figure 1. a) Map showing the extension and land-cover of the Brazilian Legal Amazon according to TerraClass 2010. Savanna-type vegetation includes cerrado, campinas and campinaranas. Cleared areas includes agricultural fields, pasture lands and deforested areas. b) Map of degraded and burned area detected from 2007 to 2010.

2.2. **Datasets**

We used degradation maps provided by the DEGRAD project (http://www.obt.inpe.br/degrad/dados/) which monitors the degradation of the Brazilian Amazon forest caused by wood extraction or by recurrent fires (INPE, 2013b). Forest areas likely to become deforested where the canopy has not been totally removed are considered by DEGRAD as degraded areas. It is based on the Landsat Thematic Mapper and CBERS satellites to detect clearings of at least 6.25 ha size annually from 2007 to 2010 at 60 m spatial resolution.

Annual deforestation maps for the same period were obtained from the PRODES project which has been monitoring Brazilian Amazon deforestation since 1988 (INPE, 2013a, http://www.dpi.inpe.br/prodesdigital/prodes.php). PRODES combines satellite data from the Thematic Mapper (LANDSAT), DMC (Disaster Monitoring Constellation) and CCD (CBERS) sensors, and their successors for recent years, and detects clearings of at least 6.25 ha where deforestation by clear cutting has occurred at 60 m spatial resolution and one map each year.

The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the polar orbiting Terra and Aqua satellites maps fire affected areas since 2000 (Roy *et al*., 2008). We used the re-projected monthly Geotiff version of MODIS collection 5 Burned Area Product (MCD45, National Aeronautics and Space Administration, University of Maryland FTP server: ftp://ba1.geog.umd.edu) from 2007 to 2010 (500-m resolution, windows 5 and 6).

Land-cover maps of the Legal Amazon were produced by the TerraClass project (http://www.inpe.br/cra/projetos_pesquisas/terraclass2008.php) showing a very detailed land-use classification in 15 categories at 30-m resolution with data generated from the interpretation of images Landsat/TM5 for the years 2008 and 2010 (Almeida *et al*., 2009; INPE and EMBRAPA, 2013).

2.3. **Data analysis**

We worked with the geographical information system (GIS) package ArcGIS 10.1 (Esri) to conduct all digital spatial and temporal analysis. While TerraClass and DEGRAD files were provided in Esri shapefile format, burned area files needed a preliminary transformation into polygon shapefiles. Burned and degraded area maps were overlaid for computing the temporal and spatial relation between them for each year of the study period (2007-2010), after aggregating degradation data to 500 m to fit its resolution to the fire data. The same overlay operation was applied to the degraded area layers and land-use maps (in 2008 and 2010) to track their evolution over time. Potential escaping fires from pasture fields, agricultural lands and deforested areas into the forest contributing to degradation were evaluated by creating buffer zones of different size (from 0.5 to 3 km, every 0.5 km) around the burned areas occurring in managed lands to examine the proportion of forest patches that were burned, and therefore classified as degraded areas (hereafter referred to as fire-related degraded area) within each buffer. The coordinate system of the files was converted to the geographic South American Datum 1969, when working with Amazonia, or to the state corresponding projected coordinate system according to the Universal Transverse Mercator scheme. This way a proper fit between the different information layers was achieved and accurate area calculations of the polygons were performed.

3. **Results**

In the period from 2007 to 2010, 395549 km² of burned area were detected in the Brazilian Legal Amazonia (8% of the territory) and 64308 km² of forest were registered as degraded (2% of the forested area within the study region in 2010). Both variables showed an uneven spatial distribution. Burned area was concentrated in southern Mato Grosso, Tocantins and southern Maranhão, which corresponds to the extension of the savannah-type vegetation, while degraded area was mainly located along the arc of deforestation (Rondônia, northern Mato Grosso, eastern Pará and northern Maranhão) (Figure 1b). The highest amount of burned area was found in 2010 (177615 km²), while the maximum amount of degraded area was detected in 2008 (27478 km²) (Figure 2a) with all nine states in the region presenting the same trend (Figure 2b). Most burned area was observed in the state of Mato Grosso contributing 44% of the total, followed by Tocantins (30%), Maranhão (13%) and Pará (12%). The states contributing the greatest amounts of degradation were Mato Grosso (51%), Pará (27%) and Maranhão (14%) (Figure 2b). In 2007 and 2010, the two high fire years of the period, 11% of the degraded area was detected as burned in the same year, while figures were lower than 1% in 2008 and 2009 (Figure 3a).

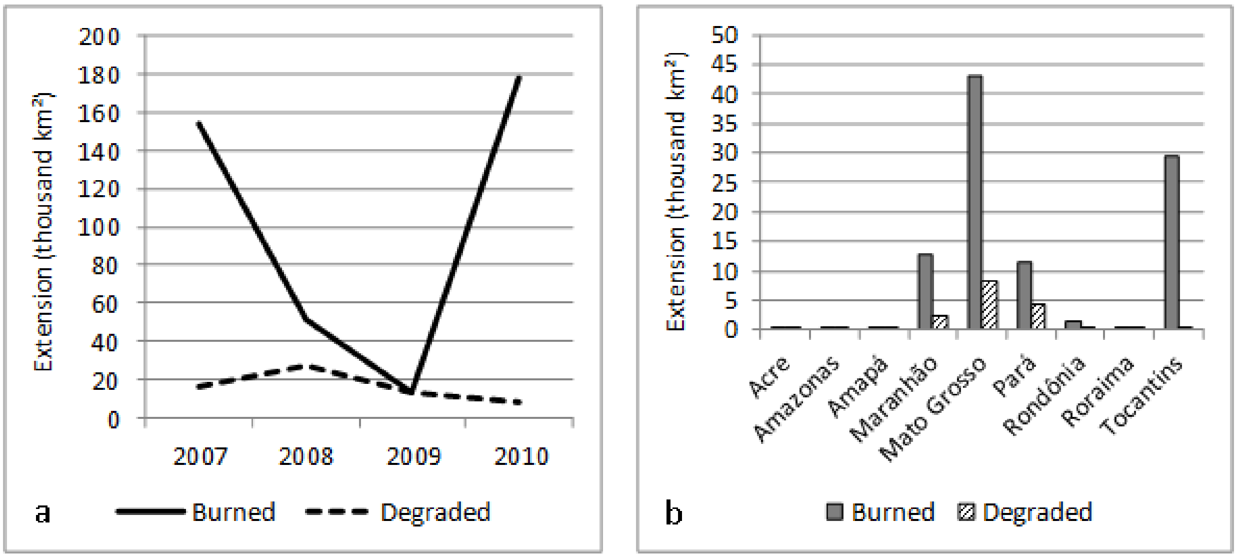

Figure 2. a) Annual burned (solid line) and degraded (dashed line) area for2007-2010 in the Brazilian Legal Amazon (in thousand km²). b) Amount of burned and degraded area in the different states (in thousand km², averaged over the period 2007-2010).

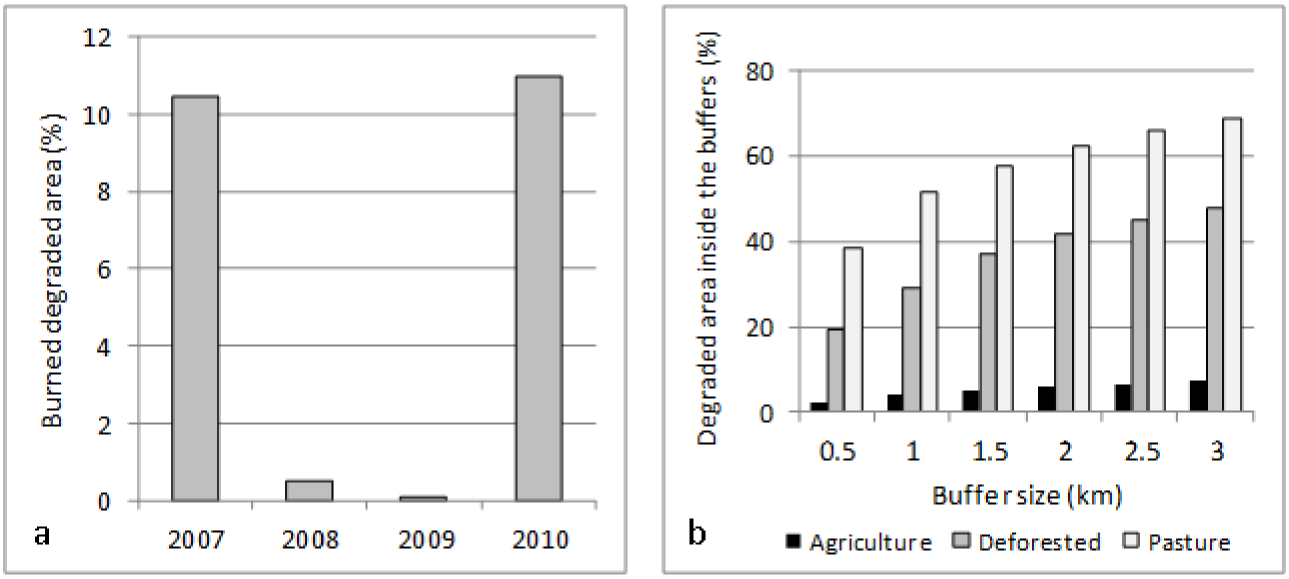

Figure 3. a) Percentage of degraded area that was also detected as burned area by MODIS in the same year. b) Percentage of fire-related degraded area that was connected to burnings in managed lands and deforested areas averaged over 2008 and 2010 in the Brazilian Legal Amazonia.

Fires escaping from agricultural fields in the vicinity of forest may cause between 2 (0.5-km buffer) and 7% (3-km buffer) of forest degradation, which means that between 6 and 31 km² of the fire-related degraded area were within the 0.5-km buffer and 3-km buffer zone, respectively, established around the burned area polygons in agricultural lands, averaged over 2008 and 2010 (Figure 3b). The proportion of the fire-related degraded area that overlapped the buffers delimited around pasture burned area polygons was higher for all the buffer sizes compared to agricultural buffers, between 39 and 69% of the fire-related degraded area (between 107 and 300 km²), averaged over 2008 and 2010 (Figure 3b). Fires occurring in deforested areas may be responsible for 19 to 48% of the forest degradation caused by fire (between 73 and 191 km²), averaged over 2008 and 2010 (Figure 3b). Concurrent with the greatest annual burned area figures in the period, the year 2010 presented higher overlap values between the buffers and the fire-related degraded area than 2008 for all the three land-uses: agricultural, pasture and deforested lands.

Of the degraded area detected in 2007, 23% was still considered as such one year later, 7% two years later and 3% three years later (data not shown). According to Terraclass, 84% of the forest classified as degraded in 2007 remained forest one year later. The remaining degraded area was registered in 2008 as deforestation (11%), secondary vegetation (2%), pasture (1%) and degraded pasture (1%) (Figure 4a). Three years after degradation, 80% of 2007’s degraded area was detected as forest, the proportion of deforested area decreased (3%) while the area covered by areas in regeneration after being deforested and used for agriculture or pasture (7%), pasture (4%) and degraded pasture (3%) increased, and a similar extension of secondary vegetation was found (2%), compared to the figures observed in 2008 (Figure 4b).

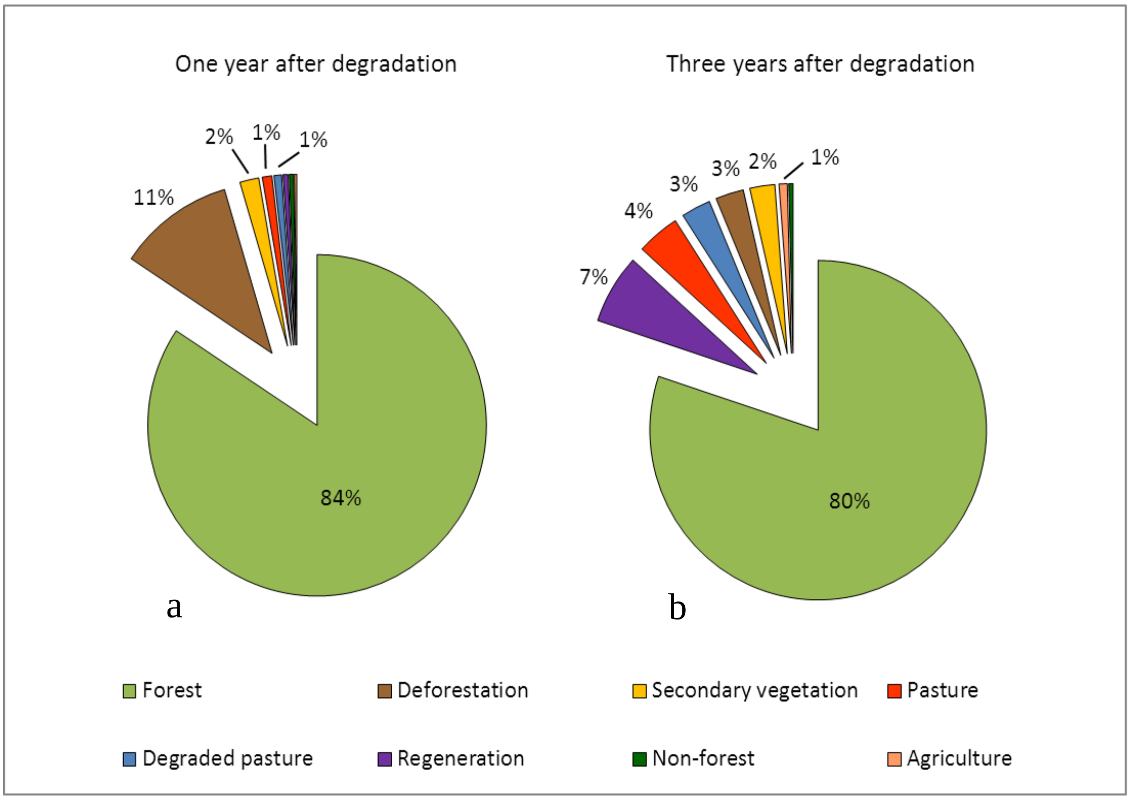

Figure 4. a) Land-use of the degraded area assigned by TerraClass one year after degradation, in 2008, and b) three years after degradation, in 2010 (averaged over the Brazilian Legal Amazonia).

4. Discussion

The above results underscore the relatively low proportion of degraded area solely related to forest fires, being 11% the maximum percentage of annual degraded area that was connected to burning events in the detection year (Figure 3a). However, it is important to consider the difficulty in obtaining accurate burned area mapping within tropical closed-canopy forest by MODIS (Giglio *et al.*, 2006), which can lead to underestimation of burning occurrence in the forest, e.g., small surface fires can be overlooked (Morton *et al.*, 2013). The analysis detected evidence of the link between degradation fires and land-use change processes. Even when considering the conservative 0.5-km buffer, 2, 19 and 39% of the fire-related degraded area may be the result of escaping fires from the adjacent agricultural lands, deforested areas and pasture fields, respectively, and the figures increase as the buffer size grows (Figure 3b). These findings support the idea of burning events becoming much more frequent and widespread across the Amazon forests as a consequence of deliberate fire use for land clearing and field maintenance (Cochrane, 2003; Cardoso *et al.*, 2009; Davidson *et al.*, 2012).
Since the forest degradation drivers contemplated by the DEGRAD system are selective logging and fire (INPE, 2008), the results of the fire vs. degraded area analysis indicated a stronger influence of selective logging in degradation. Unfortunately, we do not have logging data for the study period to confirm this premise, but different studies have identified logging as the process responsible for the largest proportion of forest degradation (Matricardi *et al.*, 2010). Kissinger *et al.*, (2012) in their report for REDD+ policymakers stated that unsustainable logging accounted for more than 70% of forest degradation in Latin America. Moreover, once disturbed by selective logging activities, the amount of dead slash or dried biomass increases and forest becomes more susceptible to fire (Uhl and Kauffman, 1990; Holdsworth and Uhl, 1997).

Around 80% of the degraded forest was still classified as forest one and three years later (Figure 4). After 12 years, Matricardi *et al.* (2010) found that 70% of the total forest area disturbed in their study area in the state of Mato Grosso had sufficiently recovered to become undetectable using satellite data. Degraded forests can often remain in a degraded state for long periods of time if degradation drivers remain, or if ecological thresholds have been passed, and yet remain officially defined as forests for classification purposes (Murdiyarso *et al.*, 2008; Sasaki and Putz, 2009), thus, regrowing vegetation can lead to misclassification in the absence of accompanying field data. The climax of forest regeneration seems to be 3 to 5 years following logging activities and 3 to 10 years after a forest fire event (Matricardi *et al.*, 2010), which explains why Stone and Lefevre (1998) observed in their study in the state of Pará that within 3 to 5 years degradation signal by selective logging was obscured by the regenerating forest canopy. Even though most of the degraded forest regenerated, 11% was deforested one year later, which is comparable with previous estimates of 16% due to logging alone by Asner *et al.* (2006) for the early 2000s, when deforestation rates were higher.

Recent research has contributed to substantial improvements in remote sensing based techniques to evaluate extent and impacts caused by selective logging and forest fires (Matricardi *et al.*, 2010; Morton *et al*., 2011b; Andersen *et al.*, 2013). However, a large-scale and long-term evaluation of processes causing forest degradation is still lacking, but is required to understand ecological and climate-related consequences of tropical forest impoverishment through logging and fire.

5. Conclusions

Based on these research results we can conclude that forest degradation is not mainly controlled by fire, which suggests that the major driver in the Brazilian Amazonia is selective logging. The occurrence of fire in the forest, in most of the cases, is the result of land-use change processes, and escaping fires from pasture management play a crucial role. Only a small percentage of degraded forest becomes deforested or develops to other land-uses one and three years after degradation, while the majority of it recovers and is still detected as forest. Continuous monitoring of forest degradation across tropical forests is critical for developing land management policies, as well as for an accurate estimation of carbon stocks/emissions. At the same time, global Earth system models must incorporate dynamic models of land-use change driving deforestation, forest degradation and vegetation fires for a better carbon balance simulation.

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7. References

Alencar, A., Asner, G. P., Knapp, D. and Zarin, D. (2011). Temporal variability of forest fires in eastern Amazonia. *Ecological Applications 21*, 2397-2412.

Almeida, C., Pinheiro, T., Barbosa, A., Abreu, M., Lobo, F., Silva, M., Gomes, A., Sadeck, L., Medeiros, L., Neves, M., Silva, L. and Tamasauskas, P. (2009). *Metodologia para mapeamento de vegetação secundária na Amazônia Legal.* Technical Report. Brazil's National Institute for Space Research, São José dos Campos, Brazil.

Andersen, H. E., Reutebuch, S. E., McGaughey, R. J., d'Oliveira, M. V. N. and Keller, M. (2013). Monitoring selective logging in western Amazonia with repeat lidar flights. *Remote Sensing of Environment*, doi:10.1016/j.rse.2013.08.049.

Armenteras, D., González, T. M. and Retana, J. (2012). Forest fragmentation and edge influence on fire occurrence and intensity under different management types in Amazon forests. *Biological Conservation 159,* 73-79.

Asner, G. P., Knapp, D. E., Broadbent, E. N., Oliveira, P. J. C., Keller, M. and Silva, J. N. (2005). Selective logging in the Brazilian Amazon. *Science 310,* 480-482.

Asner, G. P., Broadbent, E. N., Oliveira, P. J. C., Keller, M., Knapp, D. E. and Silva, J. N. (2006). Condition and fate of logged forests in the Brazilian Amazon. *Proceedings of the National Academy of Sciences 103,* 12947-12950.

Barlow, J. and Peres, C. A. (2008). Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philosophical Transactions of the Royal Society B-Biological Sciences 363,* 1787-1794.

Berenguer, E., Ferreira, J., Gardner, T. A., Aragão, L. E. O. C., de Camargo, P. B., Cerri, C. E., Durigan, M., de Oliveira, R. C., Vieira, I. C. G. and Barlow, J. (2014). A large-scale field assessment of carbon stocks in human-modified tropical forests. *Global Change Biology*, doi: 10.1111/gcb.12627.

Cardoso, M., Nobre, C., Sampaio, G., Hirota, M., Valeriano, D. and Camara, G. (2009). Long term potential for tropical-forest degradation due to deforestation and fires in the Brazilian Amazon. *Biologia 64,* 433-437.

Chazdon, R. L. (2008). Beyond deforestation: restoring forests and ecosystem services on degraded lands. *Science 320,* 1458-1460.

Cochrane, M. A. (2003). Fire science for rainforests. *Nature 421*, 913-919.

Cochrane, M. A. and Laurance, W. F. (2008). Synergisms among fire, land use, and climate change in the Amazon. *Ambio* 37, 522-527.

Davidson, E. A., de Araújo, A. C., Artaxo, P., Balch, J. K., Brown, I. F., Bustamante, M. M. C., Coe, M. T., DeFries, R. S., Keller, M., Longo, M., Munger, J. W., Schroeder, W., Soares-Filho, B. S., Souza Jr., C. M. and Wofsy, S. C. (2012). The Amazon basin in transition. *Nature 481*, 321-328.

FAO-ITTO (2011). *The State of Forests in the Amazon Basin, Congo Basin and Southeast Asia*. Food and Agriculture Organization, Rome. **http://www.fao.org/docrep/014/i2247e/** i2247e00.pdf

Giglio, L., van der Werf, G. R., Randerson, J. T., Collatz, G. J. and Kasibhatla, P. (2006). Global estimation of burned area using MODIS active fire observations. *Atmospheric Chemistry and Physics 6*, 957-974.

Holdsworth, A. R. and Uhl, C. (1997). Fire in Amazonian selectively logged rainforest and the potential for fire reduction. *Ecological Applications 7*, 713-725.

Houghton, R. A., Lefkowitz, D. S. and Skole, D. L. (1991). Changes in the landscape of Latin America between 1850 and 1985. I. Progressive loss of forests. *Forest Ecology and Management 38*, 143-172.

INPE (2008). *Monitoramento da cobertura florestal da Amazônia por satellite: sistemas PRODES, DETER, DEGRAD e queimadas.* Brazilian Institute for Space Research, São José dos Campos, Brazil.

INPE (2013a). *Projeto PRODES*. *Monitoramento da floresta Amazônica brasileira por satélite.* Brazilian Institute for Space Research, São José dos Campos, Brazil. http://www.obt.INPE.br/prodes/

INPE (2013b). *Projeto DEGRAD*. *Mapeamento da degradação florestal na Amazônia Brasileira.* Brazilian Institute for Space Research, São José dos Campos, Brazil. http://www.obt.inpe.br/degrad/

INPE and EMBRAPA (2013). *Projeto TerraClass*. Brazilian Institute for Space Research-Amazon Regional Center, Belém, and the Brazilian Enterprise for Agricultural Research, Brasília, Brazil. http://www.inpe.br/cra/projetos_pesquisas/ terraclass2008.php

Kissinger, G., Herold, M. and De Sy, V. (2012). *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers*. Lexeme Consulting, Vancouver.

Lambin, E. F., Geist, H. J. and Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources 28*, 205-241.

Lepers, E., Lambin, E. F., Janetos, A. C., DeFries, R., Achard, F., Ramankutty, N. and Scholes, R. J. (2005). A synthesis of information on rapid land-cover change for the period 1981-2000. *BioScience 55*, 115-124.

Malhi, Y., Wood, D., Baker, T. R., Wright, J., Phillips, O. L., Cochrane, T., Meir, P., Chave, J., Almeida, S., Arroyo, L., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Monteagudo, A., Neill, D. A., Núñez Vargas, P., Pitman, N. C. A., Quesada, C. A., Salomão, R., Silva, J. N. M., Torres Lezama, A., Terborgh, J., Vásquez Martínez, R. and Vinceti, B. (2006). The regional variation of aboveground live biomass in old-growth Amazonian forests. *Global Change Biology 12*, 1107-1138.

Malhi, Y. (2012). The productivity, metabolism and carbon cycle of tropical forest vegetation. *Journal of Ecology 100*, 65-75.

Matricardi, E. A. T., Skole, D. L., Pedlowski, M. A., Chomentowski, W. and Fernandes, L. C. (2010). Assessment of tropical forest degradation by selective logging and fire using Landsat imagery. *Remote Sensing of Environment 114*, 1117-1129.

Morton, D. C., Defries, R. S., Randerson, J. T., Giglio, L., Schroeder, W. and van der Werf, G. R. (2008). Agricultural intensification increases deforestation fire activity in Amazonia. *Global Change Biology 14*, 2262-2275.

Morton, D. C., Sales, M. H., Souza Jr., C. M. and Griscom, B. (2011a). Historic emissions from deforestation and forest degradation in Mato Grosso, Brazil: 1) source data uncertainties. *Carbon Balance and Management 6*, doi:10.1186/1750-0680-6-18.

Morton, D. C., DeFries, R. S., Nagol, J., Souza Jr., C. M., Kasischke, E. S., Hurtt, G. C. and Dubayah, R. (2011b). Mapping canopy damage from understory fires in Amazon forests using annual time series of Landsat and MODIS data. *Remote Sensing of Environment 115*, 1706-1720.

Morton, D. C., Le Page, Y., DeFries, R., Collatz, G. J. and Hurtt, G. C. (2013). Understorey fire frequency and the fate of burned forests in southern Amazonia. *Philosophical Transactions of the Royal Society B-Biological Sciences 368,* http://dx.doi.org/10.1098/rstb.2012.0163.

Murdiyarso, D., Skutsch, M., Guariguata, M., Kanninen, M., Luttrell, C., Verweij, P. and Stella, O. (2008). *Measuring and monitoring forest degradation for REDD: Implications of country circumstances*. Center for International Forestry Research (CIFOR) info briefs 16.

Nepstad, D. C., Stickler, C. M., Soares-Filho, B. and Merry, F. (2008). Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B-Biological Sciences 363,* 1737-1746.

Parrotta, J. A., Wildburger, C. and Mansourian, S. (Eds.). (2012). *Understanding relationships between biodiversity, carbon, forests and people: The key to achieving REDD+ objectives*. IUFRO World Series Vol. 31.

Pearson, T. R. H., Brown, S. and Casarim, F. M. (2014). Carbon emissions from tropical forest degradation caused by logging. *Environmental Research Letters 9,* doi:10.1088/1748-9326/9/3/034017.

Peres, C. A., Barlow, J. and Laurance, W. F. (2006). Detecting anthropogenic disturbance in tropical forests. *Trends in Ecology & Evolution 21*, 227-229.

Roy, D. P, Boschetti, L., Justice, C. O. and Ju, J. (2008). The collection 5 MODIS burned area product-Global evaluation by comparison with the MODIS active fire product. *Remote Sensing of Environment 112*, 3690-3707.

Sasaki, N. and Putz, F. E. (2009). Critical need for new definitions of forest and forest degradation in global climate change agreements. *Conservation Letters 2*, 226-232.

Simula, M. (2009). *Towards defining forest degradation: Comparative analysis of existing definitions*. FAO Forest Resources Assessment (Working Paper 154), Rome.

Souza Jr., C. M., Siqueira, J. V., Sales, M. H., Fonseca, A. V., Ribeiro, J. G., Numata, I., Cochrane, M. A., Barber, C. P., Roberts, D. A. and Barlow, J. (2013). Ten-year Landsat classification of deforestation and forest degradation in the Brazilian Amazon. *Remote sensing 5*, 5493-5513.

Stone, T. and Lefebvre, P. (1998). Using multi-temporal satellite data to evaluate selective logging in Pará, Brazil. *International Journal of Remote Sensing 19,* 2517-2526.

Uhl, C. and Kauffman, J. B. (1990). Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology 7*, 437-449.

Van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y. and van Leeuwen, T. T. (2010). Global fire emissions and the contribution of deforestation, savannah, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics 10*, 11707-11735.

UNFCCC (2008). *United Nations Framework Convention on Climate Change Report of the Conference of the Parties on its thirteenth session*, Bali. FCCC/CP/2007/6/Add.1.

Xaud, H. A. M, Martins, F. da S. R. V. and dos Santos, J. R. (2013). Tropical forest degradation by mega-fires in the northern Brazilian Amazon. *Forest Ecology and Management 294*, 97-106.