

Remote Sensing Letters

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/trsl20>

Assessment of forest degradation in Brazilian Amazon due to selective logging and fires using time series of fraction images derived from Landsat ETM+ images

Yosio Edemir Shimabukuro^{ab}, René Beuchle^a, Rosana Cristina Grecchi^a & Frédéric Achard^a

^a Joint Research Centre of the European Commission, Institute for Environment and Sustainability (IES), Ispra, Italy

^b Brazilian National Institute for Space Research (INPE), São José dos Campos, Brazil

Published online: 10 Oct 2014.

To cite this article: Yosio Edemir Shimabukuro, René Beuchle, Rosana Cristina Grecchi & Frédéric Achard (2014) Assessment of forest degradation in Brazilian Amazon due to selective logging and fires using time series of fraction images derived from Landsat ETM+ images, Remote Sensing Letters, 5:9, 773-782, DOI: [10.1080/2150704X.2014.967880](https://doi.org/10.1080/2150704X.2014.967880)

To link to this article: <http://dx.doi.org/10.1080/2150704X.2014.967880>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing,

Assessment of forest degradation in Brazilian Amazon due to selective logging and fires using time series of fraction images derived from Landsat ETM+ images

Yosio Edemir Shimabukuro^{a,b,*}, René Beuchle^a, Rosana Cristina Grecchi^a,
and Frédéric Achard^a

^aJoint Research Centre of the European Commission, Institute for Environment and Sustainability (IES), Ispra, Italy; ^bBrazilian National Institute for Space Research (INPE), São José dos Campos, Brazil

(Received 17 June 2014; accepted 15 September 2014)

A method has been developed to identify and map areas of forest degradation caused by either selective logging or fires in tropical humid ecosystems. Our study area is located in the Mato Grosso state of Brazil, in a region known as ‘Deforestation Arc’. Eight consecutive Landsat Enhanced Thematic Mapper Plus (ETM+) images were available over this study area during the dry season of 2002 (from June to October). The proposed method is based on multi-temporal image segmentation and classification of a data set of soil and shade fraction images derived from Landsat ETM+ imagery. Areas of selectively logged forest are identified and mapped from the soil fraction images, whereas burned forest areas are identified and mapped from the shade fraction images combined with a map of deforestation happening during 2002. The main benefit of this approach is the capability to discriminate selectively logged forest from burned forest, which is a very important issue for estimating carbon emissions from forest degradation.

1. Introduction

A large part of the gross emissions of carbon into the atmosphere due to land cover changes is attributable to deforestation in the tropics (Achard et al. 2014). Forest degradation, defined as long-term disturbance in forested areas (Simula 2009), is considered to represent up to 40% of the gross emissions from deforestation in the Brazilian Amazon (Berenguer et al. 2014). These emissions from forest degradation are largely compensated by carbon sinks from regrowth in logged forest or fallows of shifting cultivation, while a smaller sink is attributable to reforestation (increase in forest area) (Baccini et al. 2012; Houghton et al. 2012; Pan et al. 2011). Consequently, forest degradation is a key process for the UNFCCC REDD+ mechanism (United Nations Framework Convention on Climate Change – Reduction of Emissions from Deforestation and Forest Degradation). Indeed, the reduction of emissions of carbon from forest degradation is one of the five activities of REDD+. Logging activities (other than clear cuts) are considered as a forest degradation process in relation to REDD+ as it usually leads to a long-term reduction of carbon stocks in tropical forests. Carbon emissions from selectively logged forest have been shown to be on average equivalent to about 12% of those from deforestation (Pearson, Brown, and Casarim 2014).

The use of satellite imagery is the only feasible way to consistently monitor forest cover changes over very large regions, given the cost of field inventory in the tropics and the lack of comparable historical national forest inventory data. Assessing tropical forests

*Corresponding author. Email: yosio@dsr.inpe.br

areas with decreasing carbon stocks through remote sensing data requires fine-resolution imagery and sophisticated image analysis techniques. Landsat Thematic Mapper (TM) imagery is available over the whole tropics since the mid-1980s (Beuchle et al. 2011).

In the Brazilian Amazon, deforestation appears as forest clear cutting (INPE 2008), while forest degradation is mainly related to selective logging and forest fires (Souza et al. 2009; Asner et al. 2009; Eva et al. 2012). Forest degradation can be a precursor of deforestation especially in the Amazon basin (Numata et al. 2010; Asner et al. 2006). Our study is aimed at assessing the extent of the two main types of forest degradation in the Amazon basin using Landsat TM imagery.

Fraction images derived from Landsat TM and Enhanced Thematic Mapper Plus (ETM+) sensors have been used for the assessment of tropical forest cover, especially in the Brazilian Amazon, e.g. soil fraction images for mapping deforested areas and shade fraction images for mapping burned areas (Souza, Roberts, and Cochrane 2005; Shimabukuro et al. 2009, 2012). Fraction images derived from linear spectral mixing model (Shimabukuro and Smith 1991) have the following characteristics: (1) vegetation fraction images highlight the forest cover conditions similarly to vegetation indices such as Normalized Difference Vegetation Index and Enhanced Vegetation Index; (2) shade fraction images highlight areas with low reflectance values such as water, shadow and burned areas; and (3) soil fraction images highlight areas with high reflectance values such as bare soils and clear cuts. Consequently, our hypothesis in this study are that (1) vegetation fraction images can allow differentiating closed forest from non-forest areas, (2) shade fraction images can allow identifying burned forest, and (3) soil fraction images can allow identifying selectively logged forest.

The DEGRAD (Forest Degradation Mapping in the Brazilian Amazonia) project from the Brazilian National Institute for Space Research (INPE) has developed a method to map degraded forest through a visual interpretation procedure (INPE 2008). Souza et al. (2009) and Asner et al. (2009) developed other methodologies for automatic mapping of deforestation and forest degradation caused by selective logging and/or forest fires: ImgTools (Image processing Tools) and CLASlite (Carnegie Landsat Analysis System-lite), respectively. These three methods (DEGRAD, ImgTools and CLASlite) are based on information derived from fraction images of Landsat TM/ETM+ imagery but do not allow differentiating between selectively logged forest and burned forest.

In this context, the main purpose of our study is to develop an automated procedure based on fraction images from Landsat TM/ETM+ multi-temporal imagery for mapping and differentiating between selectively logged and burned forest areas in the Brazilian Amazon.

2. Material and method

The study area is a subset of a Landsat scene (path/row 227/068) located in the State of Mato Grosso, within the 'Deforestation Arc' of the Brazilian Amazon (Figure 1). This region is showing high deforestation rates since the late 1980s (INPE 2014), combined with intense forest degradation activities due to fire and selective logging (Eva et al. 2012). For this study, we consider all available cloud-free Landsat ETM+ images during the dry season of 2002 (from June to October). In total, eight Landsat scenes are used in our study, which were acquired systematically every 16 days at the following dates: 15 June, 1 July, 17 July, 2 August, 18 August, 3 September, 19 September and 5 October 2002 (Figure 1). We also used one Landsat ETM+ image acquired at the end of 2001 (2 October 2001): this image is used to generate an initial forest mask based on PRODES (Deforestation Assessment in the Brazilian Legal Amazonia) approach (INPE 2002).

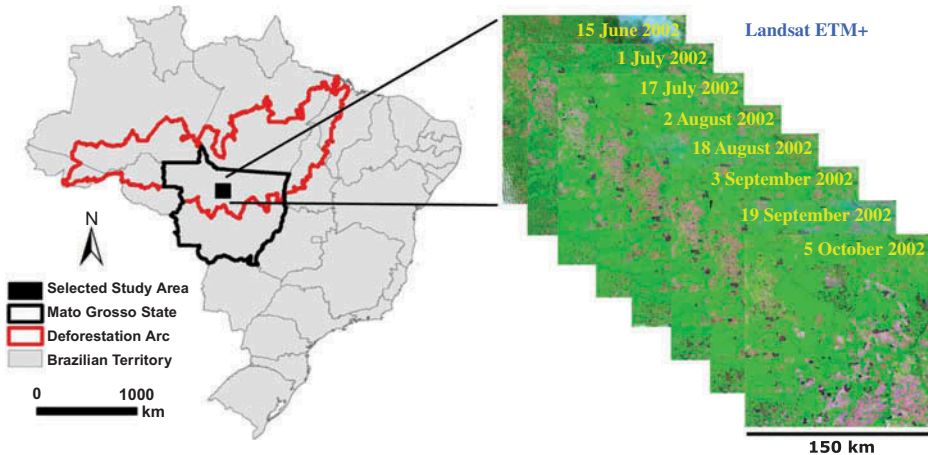


Figure 1. Location of the study area and Landsat ETM+ data set.

The proposed method for mapping the two types of forest degradation consists of four steps (Figure 2). The first step of our approach generates an initial forest mask (Figure 3), which is aimed at excluding non-forest areas (areas of historical deforestation) from the assessment of degradation. In this step, we use the Landsat ETM+ image acquired on 2 October 2001, which corresponds to the image used by INPE to produce the forest map for 2001 (INPE 2002). The second step generates fraction images (Shimabukuro and Smith 1991) for the eight Landsat ETM+ images selected during 2002 (Figure 4). Degraded forests are then assessed from the soil and shade fraction images.

The third step of our approach involves, first, segmenting a multi-temporal data set composed of soil and shade fraction images and then applying a classification process to the resulting spatial objects (segments). This step is aimed at identifying all land cover changes occurring during 2002. In the classification process, we apply a first unsupervised classification on the data set of soil fraction images, and then the resulting spectral clusters of objects are assigned as classes 'forest', 'clear cut' or 'selectively logged forest', based on the object's spectral and textural properties. Similarly, we apply a second unsupervised classification on the data set of shade fraction images, and then the resulting clusters of objects are assigned as 'unburned' or 'burned' areas from their spectral and textural properties. The results of this third step show two maps: a first map with four land cover classes – historical deforestation areas (status at the end of 2001), deforested areas (clear cuts during 2002), selectively logged forest areas (during 2002) and remaining undisturbed forest (at the end of 2002) – and a second map with three land cover classes – historical deforestation areas (status at the end of 2001), burned areas (during 2002) and unburned areas.

The fourth step combines the two resulting maps (from the third step) and generates a final map that includes two classes of degraded forest areas: selectively logged forest and burned forest. The selectively logged forest areas are identified 'manually' through a visual analysis of the soil fraction images, while burned forest areas are identified by intersecting the undisturbed forest areas layer from first map with the burned areas layer from the second map. The remaining forested areas (at the end of 2002), historical deforestation areas (status at the end of 2001) and deforested areas (during 2002) are also depicted in this final map.

Finally, our results are evaluated in two independent manners:

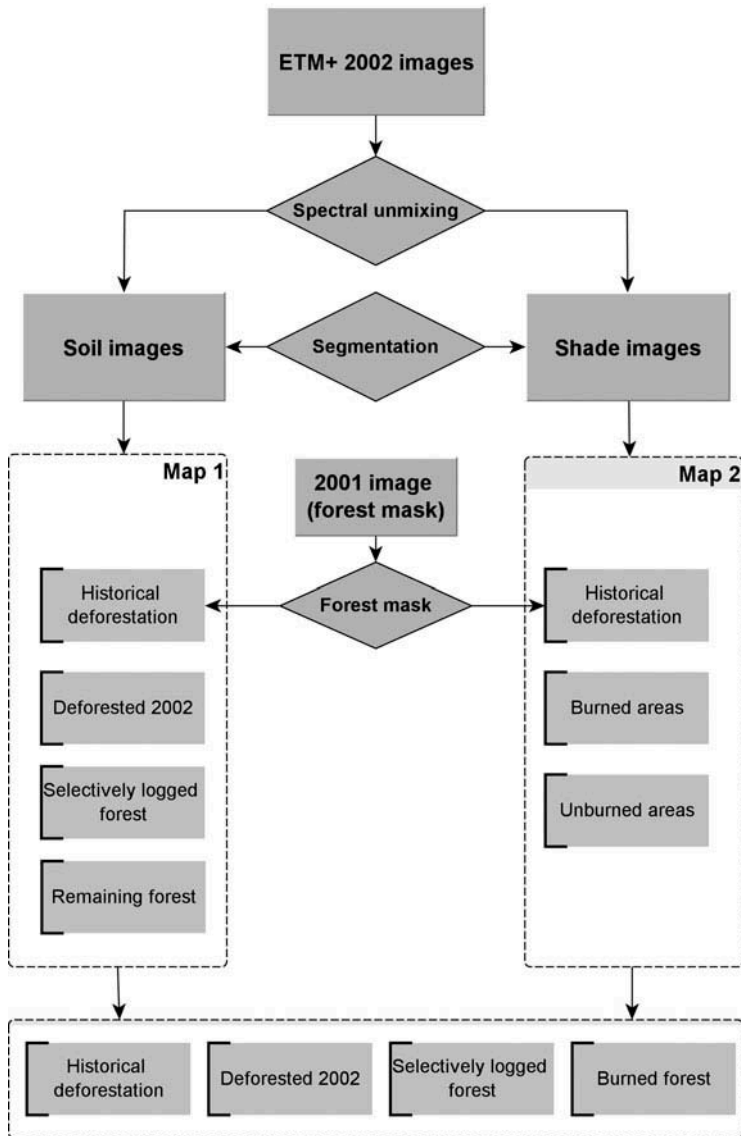


Figure 2. Methodological approach for mapping forest degradation due to selective logging and forest fires.

- we first compare our final map with INPE's PRODES map of deforestation for 2002;
- we also calculated a kappa statistic (Congalton, Oderwald, and Mead 1983; Congalton 1991; Stehman 1996) from a sample of 213 spatial objects distributed randomly within a stratification corresponding to the four land cover classes analysed in this work: 52 sample objects for layer 'Deforestation' which includes historical deforestation and deforested 2002 areas, 58 sample objects for layer 'Selectively logged forest', 52 sample objects for layer 'Forest' and 51 sample objects for layer 'Burned forest'. These objects are interpreted



Figure 3. Left panel: Landsat ETM+ imagery of 2 October 2001; right panel: Landsat imagery with overlay of non-forest mask (in yellow) adapted from INPE's PRODES data set.

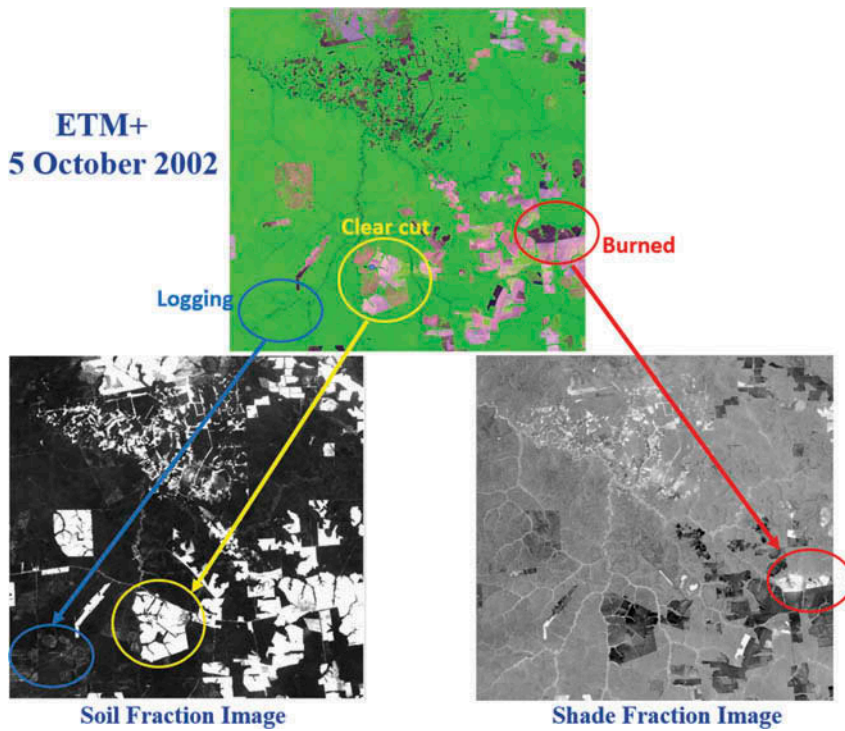


Figure 4. Soil and shade fraction images highlighting the clear cuts and selectively logged forest and burned areas, respectively.

visually by an independent expert (into the four land cover classes of our study) using two Landsat images: ETM+ scene acquired on 5 October 2002 and TM scene acquired on 13 August 2003.

3. Results

Deforested areas are easy to identify visually and map from RGB composites of Landsat ETM+ scenes (bands 3/4/5 in red/green/blue), but degraded forest areas are more challenging to depict. The procedure to map newly degraded areas is shown in Figure 5 for the first Landsat ETM+ image used in this analysis (dated 15 June 2012). Figure 5(a) shows the original ETM+ image acquired on 15 June 2002, Figure 5(b) shows the historical deforestation areas (non-forest mask) superimposed in yellow, Figure 5(c) shows the new areas deforested (in light blue) and Figure 5(d) shows the burned areas (superimposed in red) as detected in the ETM+ image. By masking the historical deforestation areas (Figure 5(b)), the area to be analysed is reduced.

The depicted burned areas within the forest (Figure 5(d)) are related either to a deforestation process or to a degradation process: in the case of deforestation, the forest cover is first fully logged (clear cut) and then the remaining vegetation is burned to allow using the land for agriculture (cropland or grassland), and in the case of degradation, the forest cover is burned through an uncontrolled fire without the removal of wood nor

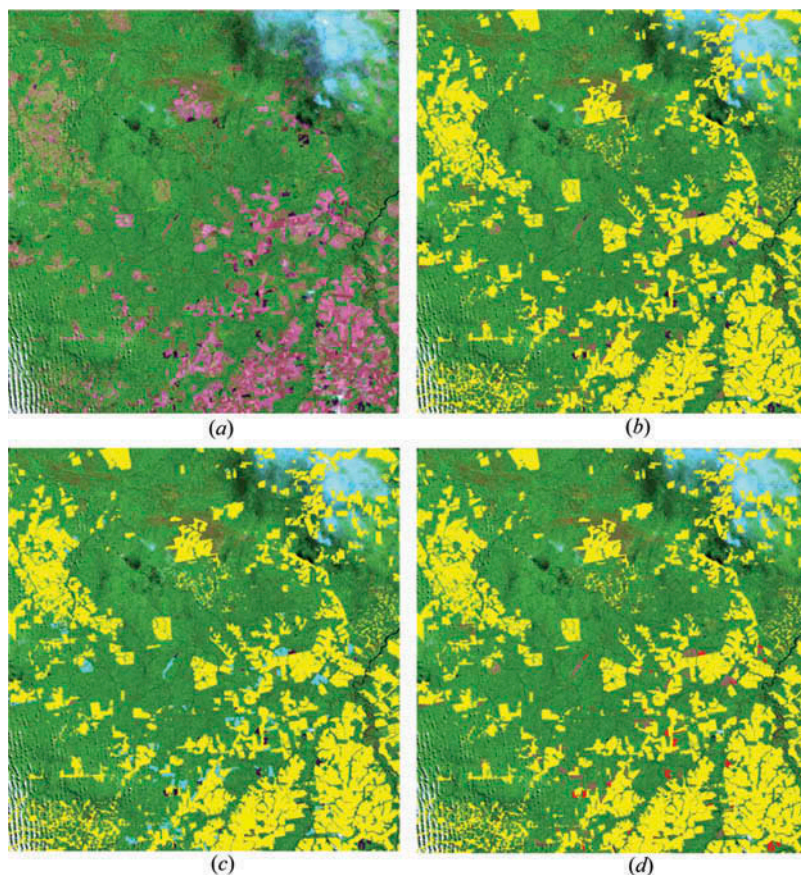


Figure 5. (Panel *a*) RGB (bands 5, 4 and 3) composite of Landsat ETM+ imagery (15 June 2002); (Panel *b*) Landsat image overlaid with a non-forest mask (yellow), representing historical deforestation; (Panel *c*) Landsat image and non-forest mask (yellow) overlaid with newly deforested areas (light blue) mapped from soil fraction image; and (Panel *d*) Landsat image and non-forest mask (yellow) overlaid with burned areas mapped from shade fraction image (red).

conversion to another land use. This makes the use of a time-series data set essential for differentiating between deforestation and degradation processes. Deforested areas will appear as non-forest areas (cropland or grassland) in the successive months or years, while burned forest (degraded forest) will quickly recover as forest regrowth.

Figure 6 shows the classification of deforested areas and degraded forest areas (selectively logged forest and burned forest) for 2002. Table 1 shows the estimated areas for all classes in comparison with the PRODES estimates. Our estimate of

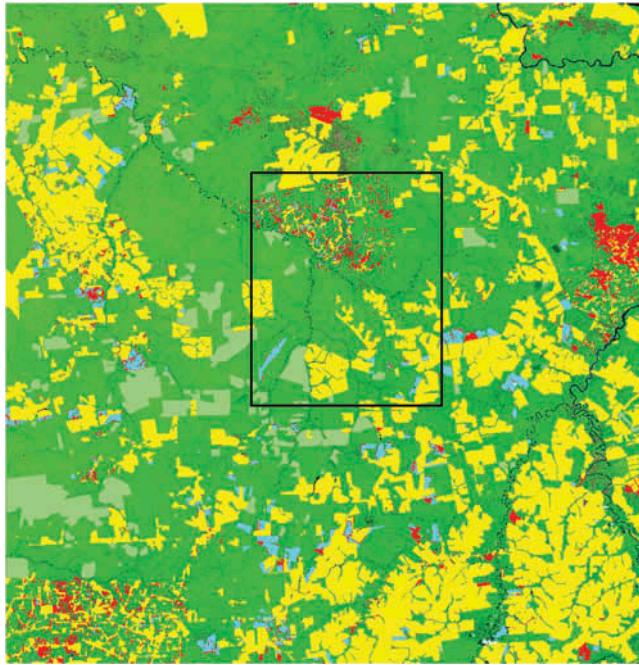


Figure 6. Undisturbed forest (dark green) and non-forest mask (yellow) with classification of new deforestation (light blue) and forest degradation areas (selectively logged forest in light green and burned areas in red) for 2002.

Table 1. Confusion matrix between land cover classes (in km²) from our study and from PRODES.

		PRODES			
		Historical deforestation (km ²)	Deforested 2002 (km ²)	Forest (km ²)	Total (km ²)
Our study	Historical deforestation (km ²)	6680	–	–	6680
	Deforested 2002 (km ²)	–	357	11	368
	Selectively logged forest (km ²)	–	–	983	983
	Burned forests (km ²)	–	206	253	459
	Forest (km ²)	–	219	16,256	16,475
Total (km ²)		6680	782	17,503	24,965

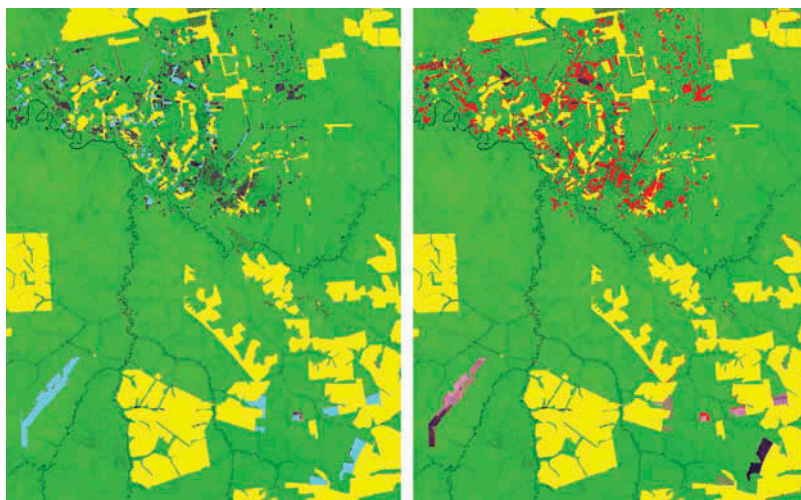


Figure 7. Subset of our study area (marked in Figure 6) showing in more detail the burned forest areas (degraded forest areas due to forest fires) appearing as dark pixels on the left panel and corresponding to the areas mapped in red in the right panel. The newly deforested areas appear as pink and dark pixels on the right panel and correspond to the areas mapped in light blue in the left panel. In both panels, the background is the Landsat ETM+ imagery of 5 October 2002 and non-forest areas (areas of historical deforestation) are masked (yellow).

deforestation during 2002 is the sum of the resulting deforested areas at the end of 2002 mapped from the full time-series of ETM+ images used in our study.

The visual analysis of the results shows that forest areas mapped as degraded due to forest fires correspond to the areas burned during 2002 which have not been detected as clear cut by the last Landsat ETM+ acquired in 2002 (Figure 7). On the other hand, deforested areas can be seen as clear cut or burned areas (Figure 7). These observations are supported by comparison with INPE's PRODES data. There is a good agreement (3% difference) between our estimates of deforestation for 2002 (i.e. corresponding only to clear cuts) at 368 km² and PRODES estimate of deforestation without burned areas at 357 km² from a total of 782 km² (Table 1). Indeed, the PRODES map of deforestation also includes 206 km² of burned forest (mapped by our method). Our method allows producing a map of deforestation with high accuracy when compared to PRODES results with a complementary map of burned forest (degraded) which does not exist as information in PRODES.

Table 2 presents the confusion matrix produced from our 213 sample objects which is used to calculate the kappa statistics. The overall accuracy is 79.3% and kappa coefficient is 0.72, which is considered a 'substantial' agreement according to Landis and Koch (1977; the 'Strength of Agreement' is considered 'substantial' when kappa is within the range 0.61–0.80). The producer and user accuracies are presented in Table 2. Most of the confusion stands between the classes burned forest (from visual interpretation) and remaining forest (from our method). This can be explained by the difficulty in detecting non-recent burned forest through our semi-automatic approach. These burned forest areas, while still showing signs of old burning (e.g. considerable portions of dark soil), contain trees already well recovered from the burning. They can be easily visually interpreted as 'burned' but cannot be detected easily in a semi-automatic way.

Table 2. Confusion matrix between land cover classes determined in our study and of visual interpretation from a sample of 213 objects.

	Land cover classes	Visual interpretation				Total	User's accuracy (%)
		Deforestation	Selectively logged forest	Forest	Burned forests		
Our study	Deforestation	51	0	1	1	53	96.23
	Selectively logged forest	0	45	0	0	45	100.00
	Forest	1	13	51	28	93	54.84
	Burned forests	0	0	0	22	22	100.00
	Total	52	58	52	51	213	
	Producer's accuracy (%)	98.08	77.59	98.08	43.14		79.34

4. Conclusions

A forest mask is essential for developing a procedure for detecting and mapping degraded forest. Using Landsat TM/ETM+ data, deforested and burned areas are easy to detect and map using a semi-automated method (Shimabukuro et al. 2009, 2012). We show here that forest degradation due to selective logging can be detected and mapped using high-resolution soil fraction images. Forest degradation due to fires (burned forest) can only be mapped using a time series of images because burned areas can also be related to a deforestation process when burning is used to clear the remaining vegetation. Our results show the feasibility to map degraded forest. In addition, the proposed method allows discriminating between selectively logged forest and burned forest, which is a very important feature for the estimation of carbon emissions. The proposed method presents a great potential for assessing forest degradation from sensors with fine spatial resolution and high-temporal frequency. Therefore, the future availability of 5-day temporal resolution of 10-m spatial resolution data from Sentinel-2 satellites is expected to improve the assessment and monitoring of forest degradation processes and consequently to facilitate implementing actions in the framework of REDD+.

References

- Achard, F., R. Beuchle, P. Mayaux, H.-J. Stibig, C. Bodart, A. Brink, S. Carboni, B. Desclée, F. Donnay, H. D. Eva, A. Lupi, R. Raši, R. Seliger, and D. Simonetti. 2014. "Determination of Tropical Deforestation Rates and Related Carbon Losses from 1990 to 2010." *Global Change Biology* 20: 2540–2554. doi:10.1111/gcb.12605.
- Asner, G. P., E. N. Broadbent, P. J. C. Oliveira, M. Keller, D. E. Knapp, and J. N. M. Silva. 2006. "Condition and Fate of Logged Forests in the Brazilian Amazon." *Proceedings of the National Academy of Sciences* 103: 12947–12950. doi:10.1073/pnas.0604093103.
- Asner, G. P., D. E. Knapp, A. Balaji, and G. Páez-Acosta. 2009. "Automated Mapping of Tropical Deforestation and Forest Degradation: CLASlite." *Journal of Applied Remote Sensing* 3: 033543. doi:10.1117/1.3223675.
- Baccini, A., S. J. Goetz, W. S. Walker, N. T. Laporte, M. Sun, D. Sulla-Menashe, J. Hackler, P. S. A. Beck, R. Dubayah, M. A. Friedl, S. Samanta, and R. A. Houghton. 2012. "Estimated Carbon Dioxide Emissions from Tropical Deforestation Improved by Carbon-Density Maps." *Nature Climate Change* 2: 182–185. doi:10.1038/nclimate1354.
- Berenguer, E., J. Ferreira, T. A. Gardner, L. E. O. C. Aragão, P. B. Camargo, C. E. Cerri, M. Durigan, R. C. D. Oliveira, I. C. G. Vieira, and J. Barlow. 2014. "A Large-Scale Field Assessment of Carbon Stocks in Human-Modified Tropical Forests." *Global Change Biology*. doi:10.1111/gcb.12627.

- Beuchle, R., H. D. Eva, H.-J. Stibig, C. Bodart, A. Brink, P. Mayaux, D. Johansson, F. Achard, and A. Belward. 2011. "A Satellite Data Set for Tropical Forest Area Change Assessment." *International Journal of Remote Sensing* 32: 7009–7031. doi:[10.1080/01431161.2011.611186](https://doi.org/10.1080/01431161.2011.611186).
- Congalton, R. G. 1991. "A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data." *Remote Sensing of Environment* 37: 35–46. doi:[10.1016/0034-4257\(91\)90048-B](https://doi.org/10.1016/0034-4257(91)90048-B).
- Congalton, R. G., R. G. Oderwald, and R. A. Mead. 1983. "Assessing Landsat Classification Accuracy Using Discrete Multivariate Statistical Techniques." *Photogrammetric Engineering & Remote Sensing* 49: 1671–1678.
- Eva, H. D., F. Achard, R. Beuchle, E. De Miranda, S. Carboni, R. Seliger, M. Vollmar, W. A. Holler, O. T. Oshiro, V. Barrena Arroyo, and J. Gallego. 2012. "Forest Cover Changes in Tropical South and Central America from 1990 to 2005 and Related Carbon Emissions and Removals." *Remote Sensing* 4: 1369–1391. doi:[10.3390/rs4051369](https://doi.org/10.3390/rs4051369).
- Houghton, R. A., J. I. House, J. Pongratz, G. R. Van Der Werf, R. S. DeFries, M. C. Hansen, C. Le Quéré, and N. Ramankutty. 2012. "Carbon Emissions from Land Use and Land-Cover Change." *Biogeosciences (Online)* 9: 5125–5142. doi:[10.5194/bg-9-5125-2012](https://doi.org/10.5194/bg-9-5125-2012).
- INPE (National Institute for Space Research). 2002. *Monitoring of the Brazilian Amazonian Forest by Satellite 1999-2000*, 18 pp. São José dos Campos: INPE.
- INPE (National Institute for Space Research). 2008. *Monitoramento da cobertura florestal da Amazonia por Satélites. Sistemas PRODES, DETER, DEGRAD E QUEIMADAS 2007-2008*. 47 pp. São José dos Campos: INPE.
- INPE (National Institute for Space Research). 2014. "Monitoramento da Floresta Amazônica Brasileira por Satélite. Instituto Nacional de Pesquisas Espaciais." Accessed April 2014. <http://www.obt.inpe.br/prodes/index.html>
- Landis, J. R., and G. G. Koch. 1977. "The Measurement of Observer Agreement for Categorical Data." *Biometrics* 33: 159–174. doi:[10.2307/2529310](https://doi.org/10.2307/2529310).
- Numata, I., M. A. Cochrane, D. A. Roberts, J. V. Soares, C. M. Souza, and M. H. Sales. 2010. "Biomass Collapse and Carbon Emissions from Forest Fragmentation in the Brazilian Amazon." *Journal of Geophysical Research* 115: G03027. doi:[10.1029/2009JG001198](https://doi.org/10.1029/2009JG001198).
- Pan, Y. D., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. W. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes. 2011. "A Large and Persistent Carbon Sink in the World's Forests." *Science* 333: 988–993. doi:[10.1126/science.1201609](https://doi.org/10.1126/science.1201609).
- Pearson, T. R. H., S. Brown, and F. M. Casarim. 2014. "Carbon Emissions from Tropical Forest Degradation Caused by Logging." *Environment Researcher Letters* 9: 034017. doi:[10.1088/1748-9326/9/3/034017](https://doi.org/10.1088/1748-9326/9/3/034017).
- Shimabukuro, Y. E., V. Duarte, E. Arai, R. M. Freitas, A. Lima, D. M. Valeriano, I. F. Brown, and M. L. R. Maldonado. 2009. "Fraction Images Derived from Terra MODIS Data for Mapping Burnt Areas in Brazilian Amazonia." *International Journal of Remote Sensing* 30: 1537–1546. doi:[10.1080/01431160802509058](https://doi.org/10.1080/01431160802509058).
- Shimabukuro, Y. E., J. R. Santos, A. R. Formaggio, V. Duarte, and B. F. T. Rudorff. 2012. "The Brazilian Amazon Monitoring Program: PRODES and DETER Projects." In *Global Forest Monitoring from Earth Observation*, edited by F. Achard, and M. C. Hansen, 153–169. New York: CRC Press.
- Shimabukuro, Y. E., and J. A. Smith. 1991. "The Least Squares Mixing Models to Generate Fraction Images Derived from Remote Sensing Multispectral Data." *IEEE Transactions on Geoscience and Remote Sensing* 29: 16–20. doi:[10.1109/36.103288](https://doi.org/10.1109/36.103288).
- Simula, M. 2009. "Towards Defining Forest Degradation: Comparing Analysis of Existing Definitions." Food and Agriculture Organization of the United Nations, Forest Resources Assessment Working Paper 154. www.fao.org/forestry
- Souza, C. M., D. A. Roberts, and M. A. Cochrane. 2005. "Combining Spectral and Spatial Information to Map Canopy Damage from Selective Logging and Forest Fires." *Remote Sensing of Environment* 98: 329–343. doi:[10.1016/j.rse.2005.07.013](https://doi.org/10.1016/j.rse.2005.07.013).
- Souza, C. M., J. Siqueira, M. H. Sales, A. Fonseca, J. G. Ribeiro, I. Numata, M. A. Cochrane, C. P. Barber, D. A. Roberts, and J. Barlow. 2009. "Ten-Year Landsat Classification of Deforestation and Forest Degradation in the Brazilian Amazon." *Remote Sensing* 5: 5493–5513. doi:[10.3390/rs5115493](https://doi.org/10.3390/rs5115493).
- Stehman, S. V. 1996. "Estimating the Kappa Coefficient and its Variance under Stratified Random Sampling." *Photogrammetric Engineering & Remote Sensing* 62 (4): 401–407.