Biogeosciences Discuss., 10, C7151–C7158, 2013
www.biogeosciences-discuss.net/10/C7151/2013/

Biogeosciences
Discussions
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Interactive comment on "Fractal properties of forest fires in Amazonia as a basis for modelling pan-tropical burned area" *by* I. N. Fletcher et al.

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Received and published: 4 December 2013

The authors would like to thank the reviewer for the time and effort put into reviewing our work. We appreciate all of the comments, and are pleased that you think the material could potentially be an important addition to the literature, given some improvements. Based on your suggestions, and those of the other reviewers, we have made considerable changes to the manuscript, and hope that they satisfactorily address any concerns you may have about the validity of the methods or reliability of the results. Below, we first of all outline the main changes we have made, and then address each of your suggestions/comments individually. We have included in each case the exact comment that we are addressing.

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Main changes to the methods

- A new distribution is used, which allows for a tail at both ends of the distribution: $n_{X\geq A} = aA^{-b}\exp(-\frac{1}{A} - \frac{A}{\theta})$ $= n_f A^{-b}\exp(1 - \frac{1}{A} + \frac{1-A}{\theta})$
- Only one parameterisation is presented, with a comprehensive explanation of its physical interpretation

Response to comments

“One cannot evaluate the burned area dataset used which is key to the work. It would be very helpful if the authors give more information about this product. In particular, how does this product compare to the burned area products they use for comparison?"

We have added in as much additional information about the dataset used as we feel could be useful (Section 2.1, pasted below). We hope that this is satisfactory.

> In this work we used a burn scar dataset for 2005 produced by Lima et al. (2009), restricted to the forested areas within the Brazilian Legal Amazonia limits, to calibrate the model. The burn scars were mapped using a Linear Spectral Mixing Model (LSMM) applied to the MOD09 daily reflectance product from Moderate Resolution Imaging Spectroradiometer (MODIS) onboard of NASA’s Terra satellite, using the red (band 1), near-infrared (band 2) and short-wave infrared (band 6) bands at a 250 m spatial resolution (Justice et al., 2002) (band 6 data was regridded from its original 500 m resolution). The MODIS images were chosen based on the following criteria: (1) Images should be within the fire season period, identified by analyz-

ing daily active fire information from MYD14 product; (2) images should be free or partially free cloud images; and, (3) images should be acquire with a view angle close to the nadir to minimize panoramic distortion.

The mapping was carried out in four steps, following the methods of Shimabukuro et al. (2009): application of a Linear Spectral Mixture Model (LSMM), segmentation of shade fraction image, unsupervised classification by regions and visual interpretation.

The LSMM was applied to the composite bands 1, 2 and 6 to generate the shade fraction image, which highlights low reflectance targets – the case of burned areas. Shade fraction images were subsequently classified in two steps. The first consisted on the application of a segmentation algorithm. The second encompassed the use of an unsupervised classification method (ISOSEG) applied to the segmented images.

For the segmentation procedure two thresholds were defined: a) the similarity threshold, a minimum threshold below which two regions are considered similar and grouped into a single polygon, and b) the threshold area, minimum area value, given in pixels numbers, for a region to be individualized. A value of 8 digital numbers and an area equal to 4 pixels were used for the similarity and area threshold, respectively. These thresholds were set based on the complexity of shape and size as well as from the mean deviations of digital number values of burnt scars samples visually identified.

After segmentation, the ISOSEG algorithm was applied to the three bands generated by the LSMM, shade, soil and vegetation with a 75% similarity limit (Shimabukuro et al., 2009). From the resulting classes, those corresponding to burned areas were merged into a single “Burn Scar" class, and the remaining classes were discarded.

All water bodies were masked out and a visual interpretation and edition

> was performed to differentiate between burn scars and terrain shadow. All maps produced for each date were combined into a single yearly map depicting the total area of burnt scars in 2005.
>
> Finally, to quantify the forest burnt area, the burnt scars map generated was overlapped by the 2005 forest mask provided by PRODES project. The final map used for the model calibration was the result of the intersection between the burnt scars and PRODES forest area maps.
>
> We compare the total area of burn scars mapped with a higher resolution map (30 m spatial resolution) derived from visual classification of Landsat 5/TM false color composite scenes for three Amazonian states following a west to east transect: 1) Acre (path 001/ row 67), 2) Amazonas (path 230/ row 65) and 3) Maranhao (path 221/ row 65). For the classification of the total burnt area for 2005 based on Landsat 5/TM data we used seven, five and six cloud free scenes acquired during the fire season for Acre, Amazonas and Maranhao, respectively. We also compare our results with the MODIS burn scar product MCD45. Overall, using the LSMM algorithm produces a total area of burn scars consistent with the higher resolution map, apart from the state of Amazonas where an underestimation is clear. Surprisingly, the MCD45 product well underestimates the burnt scar area for the regions analyzed in comparison to both Landsat 5/TM and our MODIS LSMM mapping procedure (Figure. S1, supplementary material).

“It is unclear how the active fire data was used to calculate the largest fire size." We apologise for not explaining this fully. We have added more information about this into the revised manuscript 2.3.2. The observed largest fire size in every grid cell is information that is readily available from the Lima et al. (2009) burn scar dataset. For the model parameterisation, the following explanation is now in the revised manuscript:

> The maximum size a fire can take in a grid cell is dependent on many

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factors. From a purely statistical viewpoint, the more fires in a cell, the larger $\max(A)$ is likely to be. $\max(A)$ also depends on local climatic and ecological conditions. For example, fragmented fuel or a high fuel moisture content can severely limit fire spread, while high winds and a high litter load encourage fire propagation. Additionally, the largest potential fire size is not necessarily similar to the actual achieved $\max(A)$, which makes this a difficult value to predict.

The estimate used in this model is simple: it is a log-linear function of fire counts, described by Eq. (1).

$$\log(\max(A)) \approx q \log(n_f) \tag{1}$$

This obviously takes the statistical likelihood of large fires given the sample size into account, and restricts $\max(A)$ to 1 pixel if there is only one fire, which is a reasonable assumption. Also, since fire occurrence is itself dependent on the same climatological and ecological conditions as fire spread, we would expect $\max(A)$ and n_f to covary. We see a correlation between the logarithms of the two variables of between 0.73 and 0.85, for the range of resolutions, and this relationship can be observed in Fig. (4). While the introduction of additional input variables could potentially improve the estimates of $\max(A)$, the added complexity of the model and errors present in the input datasets may counteract any potential improvement in the model performance.

The value of q is estimated for each resolution: $\hat{q} = 0.95, 0.87, 0.81$ and 0.78, for $0.5° \times 0.5°$, $1° \times 1°$, $2° \times 2°$ and $4° \times 4°$. Although there is a sizeable amount of variation in the data, and hence the errors are relatively large, there is no apparent skew to the data to suggest a more complex relationship (Fig. (4)). The value of $\hat{q}$ is clearly resolution-dependent, decreasing from 0.94 at $0.5^\circ \times 0.5^\circ$ to 0.81 at $4^\circ \times 4^\circ$. This decrease can be generalised by:

$$\hat{q} = 0.88 - 0.04\log(A_c), \tag{2}$$

where A_c is the size of the grid cell, in degrees squared.

“In general the paper is too concise and lacks discussion about methodology and implications." We have rewritten the majority of the methods, as well as the discussion and conclusion sections. The text is now more comprehensive. We have included more information about the potential uses of this model as well (see response to comment about inclusion in DGVMs).

“Active fire and burned area from MODIS are very well correlated over larger scales." We do not dispute the fact that active fire and burned area are strongly correlated, regardless of the dataset. In the burn scar dataset used to calibrate the model, burnt area is consistently approximately equal to fire counts raised to a resolution-dependent power. Our model uses only active fire as an input, therefore reinforcing this assumption. However, the model details a more complex relationship between the two products, and consistently produces BA estimates that are closer to the observed values than any estimates produced using a simple power relationship between burnt area and active fire. This can be seen using the RMSE values:

Resolution	Model RMSE	Simple power RMSE
0.5° x 0.5°	114	174
1° x 1°	244	486
2° x 2°	432	905
4° x 4°	992	2646

We thank the reviewer for the suggestion of reading Randerson et al. (2012). It proved very useful in gaining an understanding of the relationship between the two datasets used to test the model.

“The paper is framed to be useful to improve DGVMs. However, active fire data to constrain the maximum fire size and spatial distribution are not available for the future." This model is designed to be incorporated into an existing fire model framework within a DGVM. We have clarified this in the Discussion section of the revised manuscript. The exact text is given below:

> As it stands, our model could easily be substituted into an existing fire model framework, since the majority of fire models explicitly predict fire occurrence independently to burnt area. This model would replace the normal rate-of-spread equations. Such a framework could then easily be coupled to a DGVM, and, indeed, many already are.

“In Figure 6 not only the tropical forest is shown where the method was validated, but also estimates are given for savanna areas."

We excluded savanna areas from our comparison, however, due to the spatial resolution of the grid-cells from GLC2000, some savanna areas may be included in some grid cells. Another important aspect is that due to the large amount of deforestation in the tropics since 2000 (see Hansen et al., ‘High-Resolution Global Maps of 21st-Century Forest Cover Change’, Science, 2013), it is possible that some areas considered as forest would already have been deforested by 2005, and so some deforestation fires may be included in this dataset.

“In the Figures, please make use of sub- and superscript to make it easier to read" We have made all of the necessary changes to the figures. Thanks for pointing this out, we were not aware that we had neglected to do this for some of the Figures.

“To make a really strong case for the model it has to be tested against other relatively high resolution burned area assessments in other regions, or the authors

have to refrain themselves from applying their methods (validated in Brazil) to all of the tropics where fire processes can be very different from the Brazilian case."

We have now presented more information about the method for burnt scars mapping and also an evaluation of the burnt scar method for three contrasting regions in Amazonia to clarify the calibration dataset.

We agree with the referee about validating the method for other regions with higher resolution data. Despite being extremely important, this is outside the scope of this paper. We instead use a lower resolution, widely used, dataset (GFED), which incorporates already validated burnt area data from other areas to test the validity of our pan-tropical exercise.

Surprisingly, the model performs well in terms of mean values for Africa and Asia, specially for Africa where currently available moderate resolution burnt scar maps are more extensively evaluate. This comparison provides strong information that the model is coherent in terms of temporal, spatial variations and with regards to the magnitude of the values. Even more interesting is that the weakest agreement was for the area that the model was calibrated, indicating that there is a potential underestimation of fires by GFED for South American forests.

This is an important point in the discussion of the results and is a critical result to be highlighted in order to allow further evaluation of our and other available dataset. This is the only way forward for improving the estimates from tropical forest fires in global C cycle models.

Interactive comment on Biogeosciences Discuss., 10, 14141, 2013.