Anonymous Referee #1

Received and published: 20 February 2017

This paper analyzes the patterns of fire occurrence outside Legal Amazonia, covering the Northwestern part of the Amazon basin. They studied the relation of fire activity and their proximity to roads, rivers and forest edge. The results obtained in this paper highlighted the differences in fire occurrence between North and South of the Equator and within the countries analyzed. They also found significant the relation of fire occurrence with roads, rivers and forest edge. The paper is well written and organized, although more information should be included in the methods section.

Major:

- The data sources should be described in more detail. A brief explanation of how the databases of roads and rivers were built must be included in the text, as well as the last year they were updated and their spatial resolution.

Thank you for the suggestion. Indeed, some further explanation will be added regarding the datasets of roads and rivers. Text will change to:

- A forest/ non-forest map for 2010 derived from the 25 m global PALSAR mosaics produced by the Japan Aerospace Exploration Agency, JAXA from the Advanced Land Observing Satellite (ALOS)/ Phased array Type L-band SAR (PALSAR) data with an accuracy over 84.86% with regional variations (Shimada et al., 2014).
- For fire data we used the remotely sensed active fire detections from MODIS (MCD14DL, from both Aqua and Terra satellites download from January 2003 to January 2015) through the FIRMS (Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data, Collection 6). We only used data with confidence levels over 30% (nominal and high confidence fires as applied in Armenteras et al., 2016; Chen et al., 2013a) .We standardized fire occurrence by the area in km2 of the unit of analysis, so we used fire density (Number of occurrences per 1000 km2) as fire variable.
- Roads from CIESIN-ITOS (Center for International Earth Science Information Network - CIESIN - Columbia and Information Technology Outreach Services - ITOS - University of Georgia , 2013). This dataset is the best publicly available information up to 2010 for the region. The database was built from public domain roads data and has some topology corrected at the national level and the roads joint topologically at the country borders. The approximate scale is 1:250.000. This database shows no roads for Venezuela in the Amazonia, therefore, we removed Venezuela from the analysis of accessibility by roads.
- USGS HydroSheds data for the river network, a consistent hydrological dataset available from 3 arc second resolution for the region and publicly available. The dataset was built from the high-resolution elevation data obtained during a Space Shuttle flight for NASA's Shuttle Radar Topography Mission (SRTM) (Lehner et al., 2008).

- The authors used static maps of roads and forest distribution representative of a certain year (which is not specified in the text) to analyze the patterns of fire activity. Roads and forest cover are very dynamic land covers. Deforestation is an important phenomenon in the study area in this paper, so the uncertainty of comparing fires occurred in 2003 with a forest cover map of 2010 is too high. How can you prove that those fires occurred outside of the forest? I suggest the authors to have a look at the Global forest change map developed by Hansen et al. (2013) as an indication of forest change within the timeframe of this study.

We totally agree with the reviewer on the dynamics particularly with roads development, however currently it does not exist a yearly road dataset available for the region. In fact, the roads database used is a compilation of the best publicly available information from countries national databases comprising information of several years up to 2010. The database was built from public domain roads data and has some topology corrected at the national level and the roads joint topologically at the country borders. Is the best available information. Regarding the 2010 forest year used as a reference, we choose the Jaxa dataset because is currently the forest map with the higher resolution (25m) and minimum cloud problems for the region. Unfortunately, it does only exist for 2007-2010 and we choose the 2010 as a reference point to match year with the roads data. We will clarify this in the manuscript.

- When the authors say ”following the approach presented by Kumar et al (2014)” a short explanation of the method would help the reader follow better the methodology, specially when the work by Kumar et al. (2014) is being cited in the manuscript several times.

Thank you for your comment. We regret any confusion caused, we had really explained the Kumar methodology before but perhaps was not in the right order and wrongly cited. We will reorder the methods and bring the citation to the beginning of the methods to clarify this.

Minor:

- Page 3, line 52-53 and page 4, line 66 and 67. The almost same sentence is repeated: “fires in the Amazon occur more frequently in previously fragmented forest and are largely associated with deforestation and forest edges” and “Fire is frequently used for clearing in fragmented forests and is largely associated with forest edges.

We will remove the sentence in page 3

-Page 4 line 75. “But see”?

Thank you for the comment, we will correct this.

- Page 4 line 76. Add comma after “In this study”

Thank you for the comment, we will correct this.

- Page 5 line 110. There is a typo: interannual it’s repeated twice, I guess one of those should read intraannual.

Thank you for the comment, we will correct this.

- Page 7, line 145. Add “However, “ at the beginning of the sentence: “ annual fire density : : :”

Thank you for the comment, we will correct this.

- Page 7, line 160. Add "their distance to" before "both roads and rivers"
Thank you for the comment, we will correct this.

- Page 8, line 170. Add commas after "On the contrary"
Thank you for the comment, we will correct this.

- Page 8, line 192. Define the acronym SST
Thank you for the comment, we will correct this.

- Page 9, line 198. In my opinion the authors should choose one of the two: impacted or affected.
Thank you for the comment, we will correct this.

- Page 9, line 211. Change "above" with "apart from" before "climate there are: : :"
Thank you for the comment, we will correct this.

- Page 9, line 217. When the authors say"However and contrary to this study: : :", which study are you referring to?
We will clarify this point, we meant Kumar et al findings.

- Page 10,line 225. "Departments"?
We meant the administrative units, but we will change the word to sub regions for clarity.

- Page 10, line 239. "Armenteras and others" should read "Armenteras et al."
True. Thank you.

- Page 10, line 239-241. This sentence is repeated, the authors already give this information in lines 234-236. Please remove this sentence.
Thank you, we will remove the sentence

- Page 11, line 255. Change "fires" with "fire occurrence"
Thank you for the comment, we will correct this.

- Page 11, line 261. Define acronym REDD.
Thank you for the comment, we will correct this.

Anonymous Referee #2
Received and published: 24 February 2017
This paper used multiple datasets to examine the patterns of NW Amazon fire occurrence in response to the proximity to roads, rivers, and forest edges. A major contribution from this study is that it revealed the differing relationships between fires and forest fragmentation in different countries of this region. Overall the manuscript is well written and suitable for publication on Biogeosciences. My main concerns are in the method and discussion sections.
Major comments:
Need more explanation on the statistical tests used in this study. For example, what is ANOVA test? Is it a specific test method, or a general referral to a collection of statistical methods for the purpose of Analysis of Variance (ANOVA)? A reference to a paper or a program set would be good. The 'null model' of CFD should be explained

better so that readers can understand without resorting to Kumar et al. (2014). What's meaning of 'D-statistics' in Table 1 and Table 2?

Yes, ANOVA refers to one way Analysis of Variance tests. We will indicate this in the Methods section. We will change the text for:
We explored the effect of accessibility on fire occurrence by analyzing the proximity of detected fires to rivers and roads. We calculated the distance of each fire hotspot (the point coordinates were the center of the 1 km pixel) to the closest river and road. We followed the approach presented by Kumar et al (2014), we built Cumulative Frequency Distributions (CFD) per country of each set of distances to quantify the annual probability of occurrence of fire within a given distance of each transportation mean. Kumar et al (2014) built a grid spacing of 0.5 km as reference To evaluate the observed distributions of distances to road or river networks we followed the procedure layout by Kumar et al. (2014). A regularly-spaced 1x1 km square grid was created across the study area, including Colombia, Peru, Ecuador, Venezuela and Brazil. Next, distances from all locations in this grid to the road or river networks were calculated. These distance distributions represented our null models (i.e. the distance distributions that would result if there was no association between fires and those networks), against which observations should be compared. Finally, we applied a non-parametric Kolmogorov-Smirnov test to check for differences between the CFD of the observed distances and that of the corresponding null model on a per-country level. The two-sample Kolmogorov-Smirnov statistics (hereafter, D-statistics) measures the maximum distance between the two CFD curves being compared. That D-statistics index can vary from zero (both CFD curves show a complete overlap, i.e. they match exactly) to one (the two CFD curves do not overlap

Tables have been modified and will be included in the Supplementary Information as follows

Appendix. Pairwise distances between CFD curves for countries in Figures 4.

Table A1: Distances between CFD curves in Fig. 4A.

	Brazil	Colombia	Ecuador	Peru
Colombia	0.01			
Ecuador	0.39	0.38		
Peru	0.11	0.10	0.29	
Venezuela	0.21	0.20	0.20	0.10

Table A2: Distances between CFD curves in Fig. 4B.

	Brazil	Colombia	Ecuador
Colombia	0.29		
Ecuador	0.20	0.30	
Peru	0.09	0.23	0.15

Table A3: Distances between CFD curves in Fig. 4C.

	Brazil	Colombia	Ecuador	Peru
Colombia	0.03			
Ecuador	0.08	0.06		
Peru	0.03	0.01	0.05	
Venezuela	0.03	0.01	0.07	0.02

Table A4: Distances between CFD curves in Fig. 4D.

	Brazil	Colombia	Ecuador
Colombia	0.15		
Ecuador	0.48	0.40	
Peru	0.32	0.24	0.21

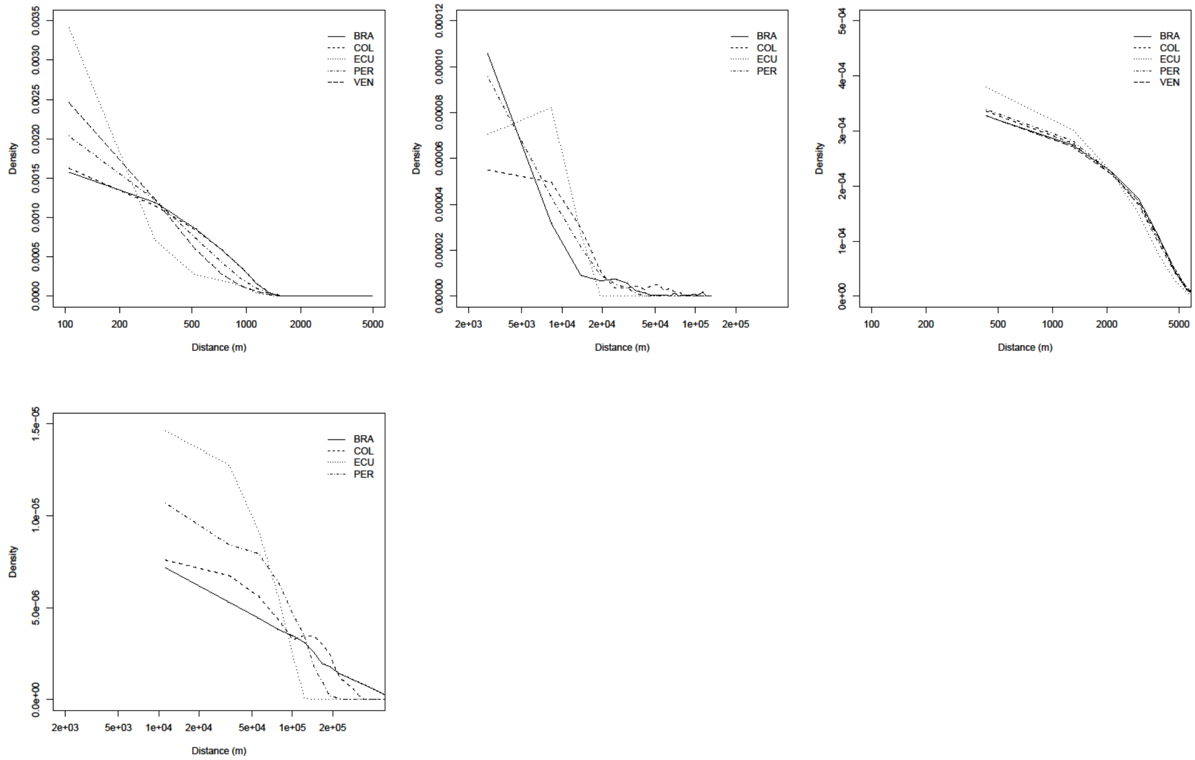
Some results deserve more discussion. The authors discussed the country-level differences in interannual variability of fires, mostly on climate perspective. However, as the authors pointed out later in the paper, a large portion of the fire occurrences in this region is associated with human activities. The socioeconomic path and its impacts on fires may vary by country to country. For example, the differences shown in Fig 2B could also be due to different levels (and starting time) of the REDD efforts, in addition to climate/weather impacts.

Yes, indeed the socioeconomic conditions of the countries must influence the dynamics, however the analysis of policies such as REDD and its adoption at country level usually takes some years to occur, and even more years to see the results and be able to make a ' correspondence analysis' between deforestation and the implementation of policies and strategies related to it. Further to undertake a policy assessment of REDD efforts a multiannual analysis including deforestation rates would be needed and we believe is out of the scope of this particular paper.

Results shown in Figs 4 and 5 are the centerpieces of this study, in my opinion (The first part of this study, i.e., the regional differences in fire occurrences, is quite obvious and well studied before). So I suggest the authors should put more efforts in the discussion of these results. For instance, are these relationships changing in different years, or at different stages of the fire season? Other than the cumulative frequency (CDF), I would also like to see the observed fire density patterns as a function to the distance to rivers/roads/forest edges.

Thank you for your interesting suggestion. The yearly analysis although extremely interesting will need to consider other variables affecting fires such as climate and also the ignition variability and types of fires that were out of the scope of this particular paper but we hope further research will add more knowledge into.

Here we present some further histograms but we believe this is a bit repetitive to be included in the document:



Minor suggestions:
P5L85 - I suppose “65W” should be “80W-65W”?
We will correct this, thank you.

P5L88 - “2,140.936 km2” looks like a typo. Should be changed to “2,140,936 km2”
Corrected, thank you.

P5L89 - Similarly, “1,558.324 km2” should be “1,558,324 km2”
Thank you for the comment, we will correct this.

P5L89-91 - Please use the same format for all areas, i.e., either using ‘XXX,XXX’ or ‘XXX’, but do not mix these two formats.
OK. Thank you for the comment, we will correct this.

P5L98 - Please be more specific on the active fire data used. There are different MODIS active fire products available on FIRMS. Please explicitly state the product name.
We used the MODIS thermal anomalies product MCD14DL, we will clarify this.

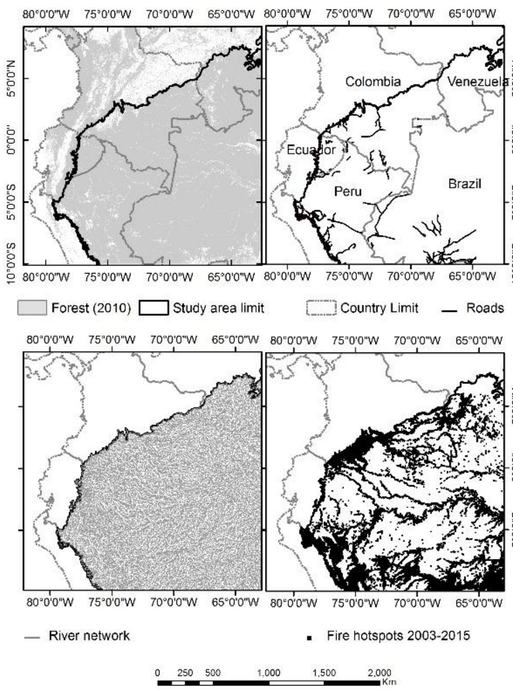
P5L99 - There’s a surplus ‘)’ in this line.
Thank you for the comment, we will correct this.
P5L110 - One “interannual” should be “intra annual”?
Thank you for the comment, we will correct this.

P6L119 - Another surplus ')' here.

Thank you for the comment, we will correct this.

P14 - Is it possible to show major roads and rivers in this figure?

The Figure will get really dense; we will incorporate this new Figure 1.



P16 - The figure in this page is the same as Fig 3 in p17.

Yes, a mistake. We will correct it

P19 - In Fig 5A, I think it is not needed to draw data corresponding to distance values of > 8000m. Looks like the cumulative frequencies in all countries have already approached 1.

We will modify the figures as follows

Figure 5A

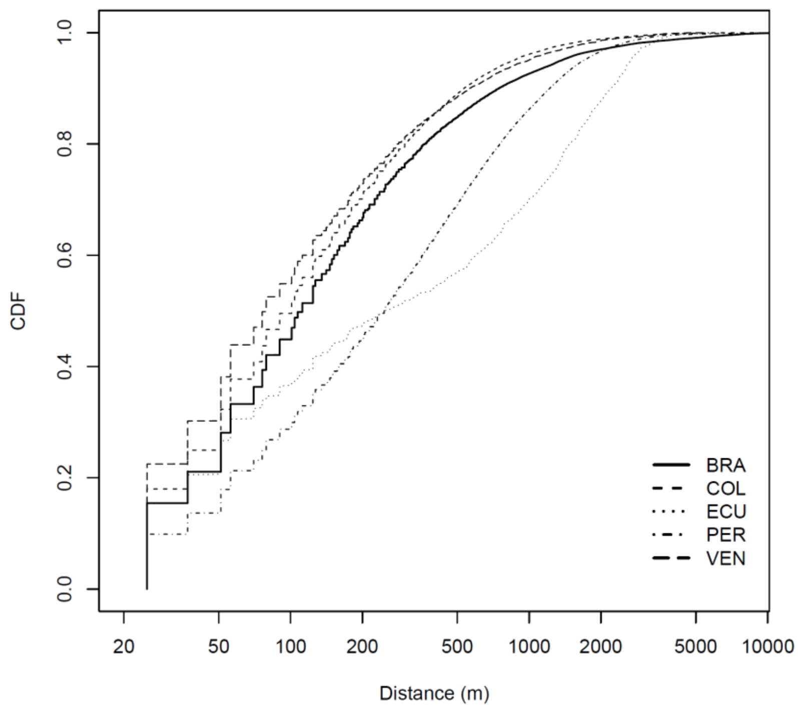
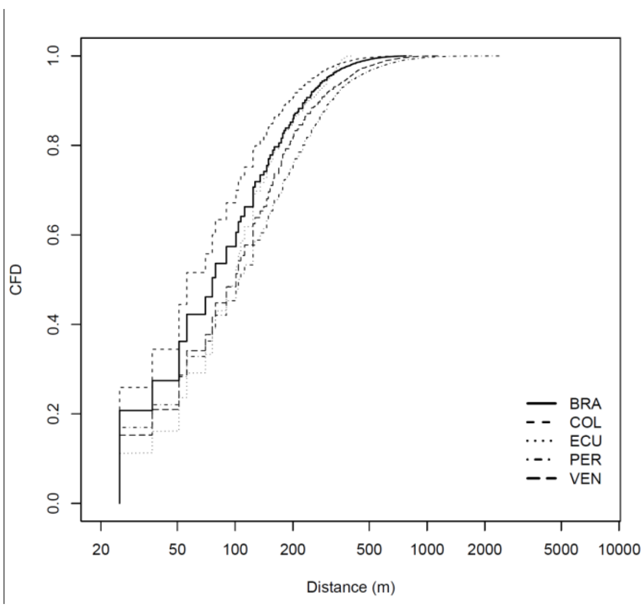

CDF
Distance (m)
BRA
COL
ECU
PER
VEN
0.0
0.2
0.4
0.6
0.8
1.0
20
50
100
200
500
1000
2000
5000
10000

Figure 5B


CFD
Distance (m)
BRA
COL
ECU
PER
VEN
0.0
0.2
0.4
0.6
0.8
1.0
20
50
100
200
500
1000
2000
5000
10000

Anonymous Referee #3

Received and published: 28 February 2017

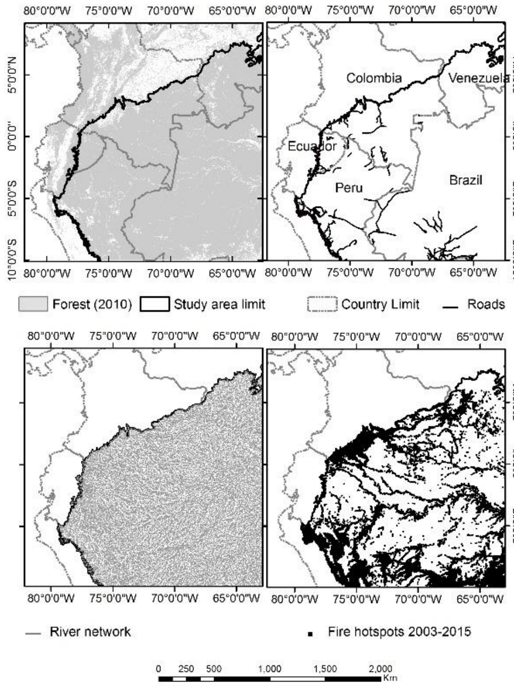
This paper reports and discusses distributions of distances between MODIS Satellite active fire detection locations to roads, rivers and forest edges in NW Amazonia. Differences in the distribution patterns by political boundaries and geographical locations are reported. The information presented is topical, important and relevant. I have major concerns in the data/analysis and results sections. Listed below are my comments.

Major

Data sources and analyses section is missing details. For eg . Was the distances computed from pixel edge or center/centroid? This has consequences as the native MODIS Active fire pixel has varying sizes depending on the scan angle (Wolfe et al. 1998; Kumar et al. 2011) and have varying confidence levels (Giglio 1999; Freebornet al. 2011). Can distances less than half a nominal 1km pixel dimensions like 300m and 500m as quoted for river networks be meaningfully interpreted ? A separate figure that shows river network and fire locations will be helpful.

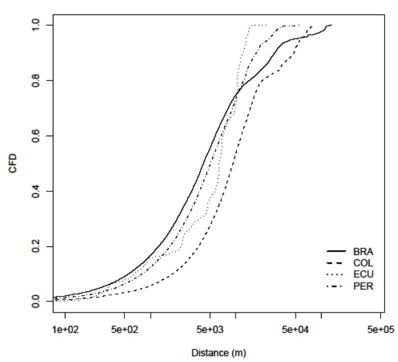
Thank you for the comment. We will clarify how distances are computed. For the fire the coordinate of the active fire is the center of a pixel of 1 km and thus the distance is from this point. In the case of forest pixels, distances are calculated from the pixel edge. We will specify this information in the methods. Regarding the meaningful distances, this is a scale issue impossible to solve with the available datasets. It is true that 300 m are within the 500 m distance of the center of the fire pixel to the edge, but it illustrates quite well the strong link of fires and rivers. We will however change the 300 m and refer to the 500m distance for consistency. I am attaching an example of a fire nearby taken from a boat this week.

We will modify Figure 1 as suggested to show the distribution of roads and rivers.



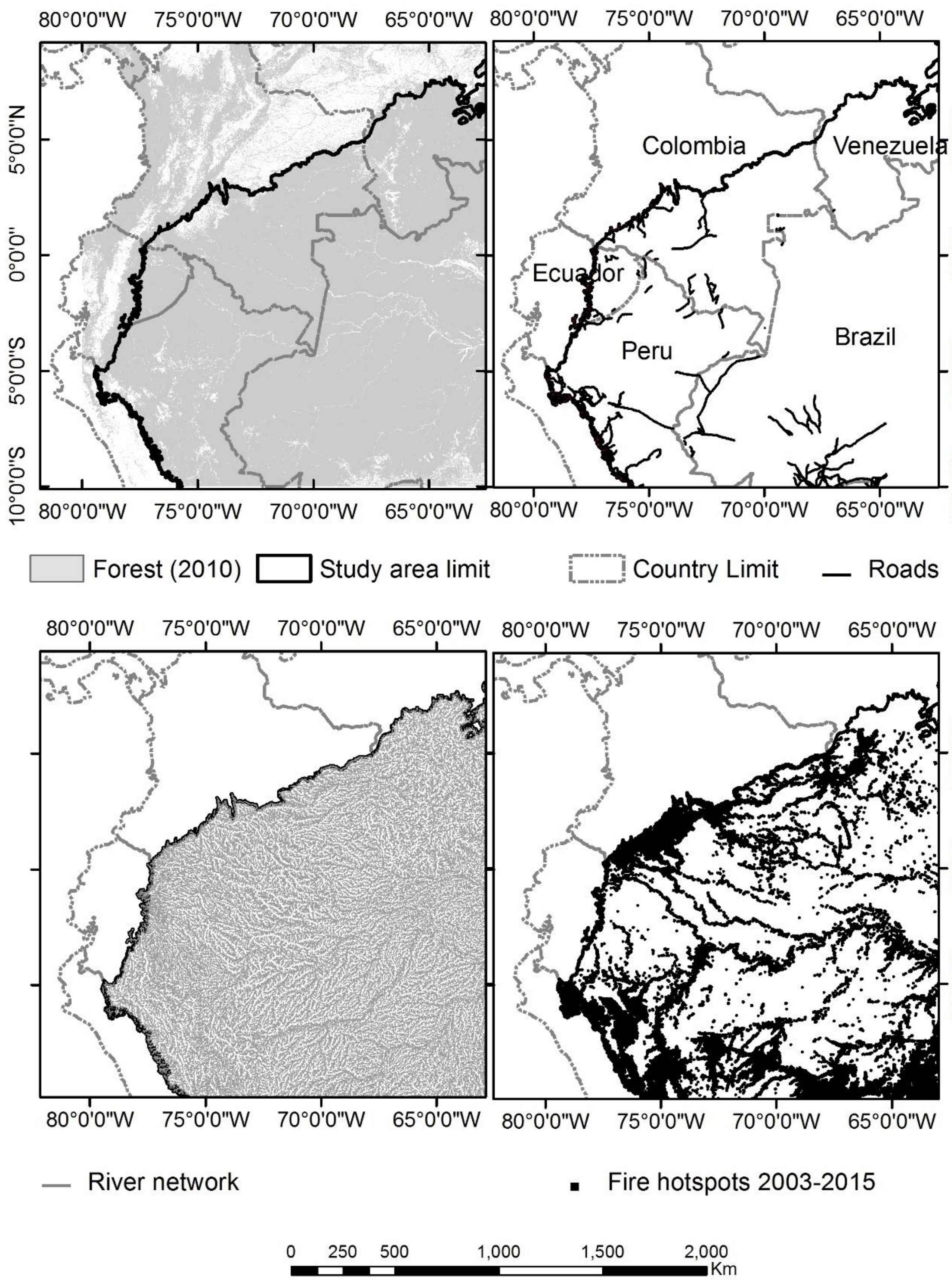
Data section (line 105-106) states that road data was not available for Venezuela, however Figure 4 B seems to show CDF curves for roads in Venezuela.

Thank you very much for your help. In the document we had calculated the distances of fires in Venezuela to roads in other neighboring countries. We will modify the figure and remove this country



Result shown in Figure 4 C is very hard to reconcile with. It's hard to believe that all 5 countries have the exact same spatial distribution of rivers (Line 169-170). An illustrative figure will help.

As you can see in the new Figure 1, the river network is dense and expands everywhere. Although the analysis indicates that in all countries the river network is similar, the analysis and the test indicates differences. It is a problem of using big amounts of data that can not be solved otherwise.


80°0'0"W
75°0'0"W
70°0'0"W
65°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
Colombia
Venezuela
Ecuador
Peru
Brazil
Forest (2010)
Study area limit
Country Limit
Roads
River network
Fire hotspots 2003-2015
0
250
500
1,000
1,500
2,000
Km

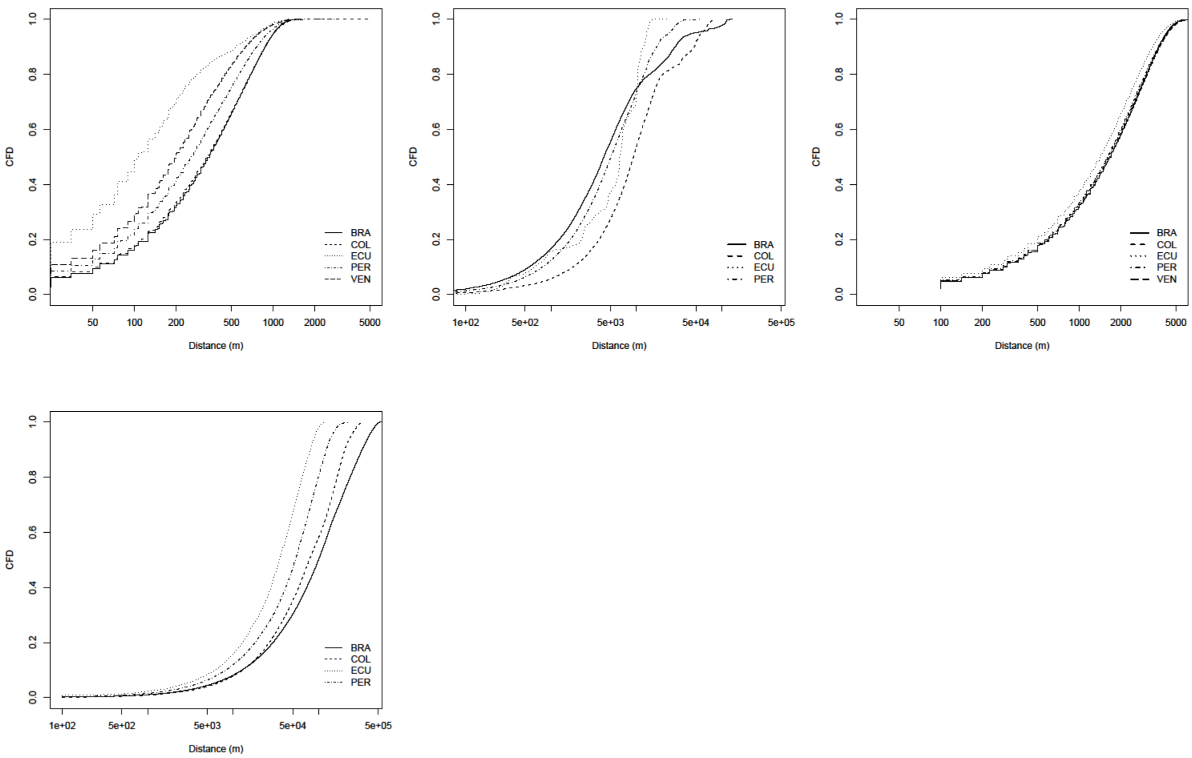
Minor

Abstract could include findings mentioned in line 195,218.

Thank you for the comment, we will correct this.

All figures need better resolutions. Need same scale for figures that are compared eg Figure 4 A-C and B-D.

They will be changed to



Line 20 this a 15 or 12 ? year study. Data used spans from 2003-2015 as mentioned in data sources and analyses.

Thank you for the comment, we will correct this.

Line 64 – 65 Barber et al. 2104 and Cochrane & Barber 2009 are only Amazonian studies need more citations to include the whole of tropics if this is true.

We will specify the Amazonian focus.

Figure 1 is not clear. A separate study region showing political boundaries, rivers and roads only, and one separately with hotspots overlaid will be easier to comprehend.

We agree that it is a lot of information, other reviewer suggested to even add roads and rivers, which is a design challenge. We will incorporate a new Figure 1 to clarify and show the different layers.

Figure 3 is in duplicate on P16 and 17.

Thank you for the comment, we will correct this.

Line 101 incorrect terminology for detection confidence (0-100 split into low-confidence, nominal confidence and high confidence (https://earthdata.nasa.gov/c5-mcd14dl)).

Thank you for the comment, we will correct this.

Line 104 “CIESIN (Center for International Earth Science Information Network, Columbia University) ”?

Thank you for the comment, we will correct this.

Line 126 and associated paragraph possible typo CDF instead of CFD? Figures seems to carry this typo as well.

Thank you for the comment, we will correct this.

More discussion on the rationale for formulation of questions and inclusion of a question wise answer in conclusion will be helpful.

Thank you very much, we are not sure what the reviewers refers to with the inclusion of a question wise answer, however we will expand the rationale for formulation of questions. Text to be added:

Because of the high variability of both environmental conditions and human dimensions, there is an imperative need to untangle the regional dynamics across the different countries

Interactive comment on “Changing patterns of fire occurrence in proximity to forest edges, roads and rivers between NW Amazonian countries” by Dolors Armenteras et al.

P. Fearnside (Referee)
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Received and published: 10 March 2017

In their article “Changing patterns of fire occurrence in proximity to forest edges, roads and rivers between NW Amazonian countries,” Dolors Armenteras and colleagues (2017) contribute to addressing one of the most pressing problems in Amazonian research: understanding the potential role of fire as a threat to Amazonian forest. Fires are becoming ever more frequent and more damaging because of the rapid increase in ignition sources as new roads are opened and human occupation increases, together with increased forest flammability as more forests are disturbed by logging, edge effects and extreme weather events. Climate changes already in course are increasing the frequency of severe droughts from both El Niño (Marengo and Espinosa, 2016) and the Atlantic dipole (Cox et al., 2008; Evan et al., 2009; Marengo et al., 2008, 2011). Armenteras and colleagues examine the distances of fire locations from forest edges (both for fires inside the forest and for those in cleared areas) and from access routes by road and river. Most important is the question of fire entry into forest. How frequently do fires enter, how far do they spread, and under what conditions?

The study shows a close proximity of fires to forest edges on both sides: on the forest side of the edges and in the adjacent clearings. Fires on the forest side are especially close to the edge. The study’s Figure 5 indicates that on the forest side of edges, 60% of fires are within 100 m of an edge and 80% are within 200 m. These distances are well within the error of the method, meaning that many of the fires classed as forest fires near edges could really be fires in the nearby clearings. Likewise, some of the fires classed as being in the clearings could really be in the adjacent forest. That fires enter Amazonian forests is obvious to anyone who has seen these events on the ground, and satellite studies are the key to quantifying the present and potential future reach of these fires. Armenteras and colleagues have provided a first step in this effort, but quantification needs to be improved with a series of next steps. Some of the tools for this are already available.

The study uses MODIS (Moderate Resolution Imaging Spectroradiometer) from NASA (National Aeronautics and Space Administration) to detect active fire. The data was from MODIS active fire data collection 5 downloaded from the Fire Information for Resource Management System (FIRMS). In 2016 NASA replaced this dataset with Collection 6, available since September 2015 with data for imagery beginning in November 2000 (for Terra) and from July 2002 (for Aqua) (NASA, 2017a). The active-fire data from FIRMS has 1 km resolution (NASA, 2017b). The manuscript does not specify which MODIS product was used (including whether it is “near real time” or one of the datasets posted 3 months later with many geopositioning errors corrected). The 1-km resolution of the active-fire data available at the time of the study is a severe limitation. Beginning on 8 January 2016 NASA began releasing improved near real time (NRT) data with 375 m resolution (VII-RS) (NASA, 2017c).

All of these datasets report the presence of absence of at least one active fire within each pixel. The location of the fire is given as the center of the pixel. With a 1 km _ 1 km pixel, the actual location of the fire (or fires) could be anywhere within 500 m of this center point, plus any additional uncertainty from geopositioning errors. These locational uncertainties, together with the reduced detectability of understory fires as compared to those burning in open areas, have been the main impediments to quantifying the overall reach of fire in standing Amazonian forest (Vasconcelos et al., 2013). These factors imply considerable uncertainty in the quantification of fire distances from edges and access routes, but this uncertainty does not affect the overall conclusion that most fires are very close to these features.

Thank you for all your comments. We will clarify the text and change it to

- For fire data we used the MODIS satellite active fire datasets (MCD14DL, from both Aqua and Terra sensors download from January 2003 to January 2015) through the FIRMS (Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data, Collection 6). We only used data with confidence levels over 30% (nominal and high confidence fires as applied in Armenteras et al., 2016; Chen et al., 2013a) .We standardized fire occurrence by the area in km^2 of the unit of analysis, so we used fire density (Number of occurrences per 1000 km^2) as fire variable.
- We will also clarify the fact that we use the coordinate of the center of the pixel in the text.

We agree with the reviewers comment regarding the limitations of the data and with the fact that the resolution (1-km) of the MODIS fire data is a potential limitation when analyzing these type of patterns but the overall conclusion is not affected and the uncertainty is widely distributed so the country differences are still valid. We anticipate that the improvement of these patterns with the higher resolution (375m) Visible Imaging Infrared Radiometer Suite (VIIRS). As this dataset becomes fully available, it will be critical to re-examine these relationships, at higher resolution. The archives of VIIRS data are not yet available, only weekly datasets and in any case still there is a limit of a couple of years of data so far available.

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NASA (2017c) VIIRS I-Band 375 m Active Fire Data. https://earthdata.nasa.gov/earthobservation-

data/near-real-time/firms/viirs-i-band-active-fire-data
Vasconcelos, S. S., Fearnside, P. M., Graça, P. M. L. A., Dias, D. V. and Correia, F. W. S. Variability of vegetation fires with rain and deforestation in Brazil0s state of Amazonas. Remote Sensing of Environment, 136, 199-209. http://dx.doi.org/10.1016/j.rse.2013.05.005, 2013.

Changing patterns of fire occurrence in proximity to forest edges, roads and rivers between NW Amazonian countries

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Abstract

Tropical forests in NW Amazonia are highly threatened by the expansion of the agricultural frontier and subsequent deforestation. Fire is used, both directly and indirectly, in the Brazilian Amazon to propagate deforestation and increase forest accessibility. Forest fragmentation, a measure of forest degradation, is also attributed to fire occurrence in the tropics. However, outside the Brazilian Legal Amazonia the role of fire in increasing accessibility and forest fragmentation is less explored. In this study, we compared fire regimes in five countries sharing this tropical biome in the most ~~North Western~~NW part of the Amazon Basin (Venezuela, Colombia, Ecuador, Peru and Brazil). We analysed spatial differences in the timing of peak fire activity and in relation to proximity to roads and rivers using ~~15~~12 years of MODIS active fire detections. We also distinguished patterns of fire in relation to forest fragmentation by analysing fire distance to the forest edge as a measure of fragmentation for each country. We found significant hemispheric differences in peak fire occurrence with the highest number of fires in the South in 2005 vs 2007 in the North. ~~we~~Despite this, both hemispheres are equally affected by fire. We also found difference in peak fire occurrence by country~~ with fire peak~~. Fire peaked in February in Colombia and Venezuela~~ in February; peak fire~~, whereas it peaked in September ~~for~~in Brazil and Peru~~;~~, and finally Ecuador presented two fire peaks in January and October. . We confirmed the relationship between fires and forest fragmentation for all countries; and also found significant differences in the distance of fire to forest edge for each country. Fires were associated to roads and rivers in most countries. These results can inform land use planning at the regional, national and sub-national scale to minimize how road expansion and subsequent access to the ~~amazonian~~Amazonian natural resources contribute to fire occurrence, and the associated deforestation and carbon emissions.

Keywords: fragmentation, accessibility, deforestation, patterns, MODIS, active fire, NW Amazon

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Introduction

Fires in the tropics are a major consequence of the interaction of climate and human activities and are becoming an increasingly important ecological factor affecting forest extent and condition (Bowman et al., 2009; Cochrane, 2009). Fire degrades forest by changing their composition and structure (Barlow and Peres, 2004), altering essential ecological processes and functions such as nutrient or hydrological cycling, or modifying the rates at which those operate (Cochrane, 2003; Marengo et al., 2008b; Morton et al., 2007). Agricultural practices that use cutting and burning as a land management technique or use fire for land clearing or grazing are usually linked to tropical deforestation (Fearnside et al., 2009; Kirby et al., 2006; Lima et al., 2012; Nepstad et al., 2001). Most recently large scale industrial agriculture was related to the use of fire (Brando et al., 2013). Increasing demands for agricultural land and forest-related products has enhanced the link of fire to tropical deforestation by enabling conditions related to increased accessibility to forests (Barber et al., 2014; Laurance et al., 2002) and changing climatic patterns (Aragao et al., 2008; Flannigan et al., 2009; Malhi et al., 2008). Fires in the region can be broadly classified in maintenance, deforestation and forest fires with different temporal patterns related to climate conditions but in some cases to the ignition cause i.e. maintenance fires in Brazil are lit every 2-4 years (Roy and Kumar, 2016)

Fire occurrence in the tropics has a particular pattern: in Latin America it has been established that north of the equator the fire season is between December and February while in the south it is between May and July (Chuvieco et al., 2008). However, unusual fire events are occurring more frequently and more intensely in the Amazon basin and have been associated to extreme climatic events such as the El Niño Southern Oscillation (ENSO) (Aragão et al., 2007; Ray et al., 2005) or the warm tropical North Atlantic Oscillation (NAO) (Marengo et al., 2008a; Phillips et al., 2009) and also to the occurrence of extreme drought years (Asner and Alencar, 2010; Brown et al., 2006; Lewis et al., 2011; Malhi et al., 2009; Marengo et al., 2008b).

In the Amazon, the increasing frequency and intensity of fires has many consequences locally, regionally, and globally. Fluctuations in biomass in the Amazon have a significant impact on atmospheric concentrations of CO_2 (Phillips et al., 2009)(Phillips et al., 2009) that contribute to global warming. Fires also cause a reduction in above ground biomass (Cochrane and Schulze, 1999; Kauffman and Uhl, 1990)(Cochrane and Schulze, 1999; Kauffman and Uhl, 1990), primary production (Kinnaird and O'Brien, 1998), loss of(Kinnaird and O'Brien, 1998), biodiversity, and disruption of regional water and energy cycles (Salati, 1987; Salati and Vose, 1984).(Salati, 1987; Salati and Vose, 1984). Despite the importance of fire occurrence in the Amazon, there is a lack of knowledge of the significance of both climate and landscape characteristics driving fire patterns, especially for those sub regions outside legal Amazonia. Rainfall patterns in the Amazon basin have high heterogeneity (Marengo, 1992; Marengo and Tomasella, 1998). Northwestern Amazonia, in particular, is one of the wettest tropical rainforest regions with ca. 3000 mm of rain per year and has a shorter/weaker dry season than Southwest, Southeast or Central Amazonia (Malhi and Wright, 2004).(Malhi and Wright, 2004).

Throughout the tropics, road development increases the susceptibility of forests to deforestation and forest fragmentation by exposing forest edges to increasing levels of disturbances particularly in the Amazon (Barber et al., 2014; Cochrane and Barber, 2009). Fire is frequently used for clearing in fragmented forests and is largely associated with forest edges (Cochrane, 2001; Cochrane and Laurance, 2002). Distance from forest edges influences fire occurrence and intensity (Cochrane 2003; Armenteras and others 2013). The combination of road development, forest deforestation, and fragmentation make tropical forests more vulnerable to fires, especially under expected climate change (Cochrane, 2003). Recent studies showing forest accessibility (from both roads or rivers) as enabling conditions for fires and using fire as a proxy for deforestation are focused mostly in the Legal Amazon (Adeney et al., 2009) or in the Brazilian tropical moist forest biome, largely ignoring the Amazonian territory under other sovereignties (Kumar et al., 2014). Little is known about factors which influence fire dynamics and patterns in NW Amazon, or about the links between fires to deforestation and fragmentation in the Ecuador, Peruvian and Venezuelan parts of the Amazon with some data in Colombia (Armenteras and Retana, 2012; Armenteras et al., 2011). The shared territory does not have the same land use policies and climate action plans nor the same economic or infrastructure development (i.e. road construction). Because of the high variability of both environmental conditions and human dimensions, there is an imperative need to untangle the regional dynamics across the different countries. In this study, we analysed the dynamics and patterns of fires in the most NW part of the Amazon basin to highlight regional differences in patterns of fire occurrence in relation to accessibility and forest fragmentation between neighbouring countries. To achieve this, we addressed the following questions: i) are temporal patterns of fire occurrence in NW Amazon tropical forests influenced by its latitudinal position (North/South) and/or the country of occurrence?, ii) are fire occurrences detected in NW Amazon influenced by accessibility and do they differ between countries? and, iii) are there differences between countries in the effect of forest fragmentation (i.e. edge effect) on fire occurrence?

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Methods

Study site

The study area (Figure 1) corresponded to the northwestern (80°W-65°W, 10°S-6°N) part of the Amazon shared by Colombia, Ecuador, Peru, Venezuela, and Brazil. The most northern and western limit was delimited using a biogeographic limit corresponding to the South American tropical and subtropical humid forest biome (UNEP, 2009).(UNEP, 2009). The total study area contained approximately 2,140.,936 km^2 of land of which 582,612 km^2 are located north of the Equator and 1,558.,324 km^2 to the south. The largest area belonged to Brazil (41% or 885-,459 km^2), followed by Peru (26%, 559-,709 km^2) and Colombia (21% or 451-,847 km^2), and finally Venezuela and Ecuador with a 8% (173-,966 km^2) and 3% respectively (69 955 km^2).

Data sources and analyses

We used the following data sources:

- A forest/ non-forest map for 2010 derived from the 25 m global PALSAR mosaics produced by the Japan Aerospace Exploration Agency, JAXA from the Advanced Land Observing Satellite (ALOS)/ Phased array Type L-band SAR (PALSAR) data with an accuracy over 84.86% with regional variations (Shimada et al., 2014).
- For fire data we used the remotely sensed active fire detections from MODIS (MCD14DL, from both Aqua and Terra satellites download from January 2003 to January 2015) through the FIRMS (Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data, Collection 6). We only used data with confidence levels over 30% (nominal and high confidence fires as applied in Armenteras et al., 2016; Chen et al., 2013a) .We standardized fire occurrence by the area in km^2 of the unit of analysis, so we used fire density (Number of occurrences per 1000 km^2) as fire variable.
    - Roads from CIESIN-ITOS (Center for International Earth Science Information Network - CIESIN - Columbia and Information Technology Outreach Services - ITOS - University of Georgia , 2013). This dataset is the best publically available information up to 2010 for the region. The database was built from public domain roads data and has some topology corrected at the national level and the roads joint

topologically at the country borders. The approximate scale is 1:250.000. This database shows no roads for Venezuela in the Amazonia, therefore, we removed Venezuela from the analysis of accessibility by roads.

- USGS HydroSheds data for the river network, a consistent hydrological dataset available from 3 arc second resolution for the region and publically available. The dataset was built from the high-resolution elevation data obtained during a Space Shuttle flight for NASA's Shuttle Radar Topography Mission (SRTM) (Lehner et al., 2008).

To examine the temporal patterns of fire occurrence, we first explored the long term patterns of fire (Jan 2003-Jan 2015) to describe both ~~interannual~~intraannual and interannual variability. We tested for differences in fire occurrence between those occurring north and south of the Equator using a paired two sample t ~~tests and among countries by means of~~test. We also used an ANOVA ~~tests~~test to ~~detect the effect of its~~check for differences in fire occurrence between latitudinal position~~ and the country~~, and another ANOVA test to evaluate the differences between countries.

We explored the effect of accessibility on fire occurrence by analyzing the proximity of detected fires to rivers and roads. We calculated the distance of ~~all~~each fire ~~hotspots~~hotspot (the point coordinates were the center of the 1 km pixel) to the closest river and road. ~~We~~We followed the approach presented by Kumar et al (2014), we built Cumulative Frequency Distributions (CFD) per country of each set of distances to quantify the annual probability of occurrence of fire within a given distance of each transportation mean. ~~For this reason we also developed grids~~Kumar et al (2014) built a grid spacing of ~~theoretical~~ 0.5 km as reference To evaluate the observed distributions of distances to ~~the explanatory~~ road ~~and~~or river networks we followed the procedure layout by Kumar et al. (2014). ~~creating a~~ A regularly-spaced ~~geographic grid of 1 km apart locations (2,254,046 points)~~ 1x1 km square grid was created across the study area~~ of~~, including Colombia, Peru, Ecuador, Venezuela~~,~~ and Brazil~~) following the approach presented by Kumar et al (2014). We called this model~~ . Next, distances from all locations in this grid to the ~~null model of distances to roads and rivers, against which fire~~road or river networks were calculated. These distance distributions ~~are~~represented our null models (i.e. the distance distributions that would result if there was no association between fires and those networks), against which observations should be compared. ~~For the sake of comparison with the work of Kumar et al. (2014), the~~ Finally, we applied a non-parametric Kolmogorov-Smirnov test ~~was applied~~ to ~~test~~check for differences ~~in~~between the ~~CFDs for both~~CFD of the ~~active fire~~observed distances and that of the corresponding null model ~~for each country, with values varying~~on a per-country level. The two-sample Kolmogorov-Smirnov statistics (hereafter, D-statistics) measures the maximum distance between the two CFD curves being compared. That D-statistics index can vary from zero (~~no significant differences between two distributions~~both CFD curves show a complete overlap, i.e. they match exactly) to one (~~two distributions totally different indicating fires occurring associated to~~ the ~~explanatory variables).~~ two CFD curves do not overlap

~~We also compared the CDF curves grouped per countries. In this case, we departed slightly from the approach outlined in Kumar et al. (2014). Instead of the two-sample Kolmogorov-Smirnov test we employed the k-sample Anderson-Darling test (Scholz and Stephens, 1987), since there is no equivalent k-sample version of the former. CDF data sets were then grouped by distances to rivers, roads and fire edges. If the k-sample Anderson-Darling tests concluded that there were significant differences between at least two of the CDF curves in the group, pairwise Anderson-Darling tests were carried out between country CDF curves.~~

In order to establish a measure of forest fragmentation and to determine whether there were any differences between countries regarding the edge effect on fire occurrence (i.e. fires occurring more frequently near the forest edge), we calculated the distance of fires (i.e. pixel center) to the forest edge (~~inside or~~considered as the pixel edge), taking into account distances both towards the interior and outside the forest). We used the 2010 forest map to establish the forest edge. Similarly to the tests for accessibility to roads and rivers, we built CFD curves for the edge distances and compared them (k-sample Anderson-Darling test) both with their respective null models of distances to edges and between countries.

Results

There was high interannual variability of MODIS active fire detections (Figure 2A). The year with the highest density of fires in the North was 2007 whilst 2005 was the year with the highest number of fires in the South. Concerning the years with less fires detected, the North had ~~less fires~~fewer in 2012 whilst the ~~south~~South showed the lowest number of fires in 2011. Despite the different patterns in terms of annual average fires there was no significant difference (t test=1.0, p=0.17) between the average annual density in the ~~north~~North (mean±standard deviation: 7.5±4.6 fires/1000 km^2) and in the south of the Equator (9.0±4.8 fires/1000 km^2). ~~Annual~~However annual fire density was significantly different between countries (Figure 2B, ANOVA F=8.0, p<0.01).

Seasonal differences between the ~~northern~~Northern and ~~southern~~Southern parts of the study area were clear (Figure 3A) with the main fire season occurring between December and March in the north and between July and October in the south of the Equator. In terms of monthly variability between countries (Figure 3B), both Colombia (4.0 fires/1000 km^2) and Venezuela (2.0 fires/1000 km^2) presented February as the fire peak month of the year~~. This is not surprising~~, as expected since both have the highest proportion of their territory in the north. Brazil (3.9 fires/1000 km^2) and Peru that are mostly located in the south of the Equator had their fire peak in September (4.0 fires/1000 km^2). ~~On the other hand,~~ Ecuador, despite having most of its territory in the southern hemisphere had two peaks in January (0.37 fires/1000 km^2) and October (0.38 fires/1000 km^2~~)~~

~~Table 1 summarizes the~~). The results of the Kolmogorov-Smirnov tests (Appendix A) used to compare the CFDs of the active fires distances to transportation networks and the null model for distance of the territory within each country, the higher the values the higher the differences between those. For all countries and both roads and rivers, the pattern of fire occurrence is significantly different to their null model and, thus, for each case fire pattern was related to both roads and rivers (~~Table 1~~Appendix A).

On the other hand, Figure 4 shows the comparison ~~between countries~~ of the CFDs of the observed distributions of distances ~~of fire~~from fires to the closest ~~river~~rivers (Fig. 4A) and roads~~.~~ (Fig. 4B). There are ~~also~~ significant differences between ~~countries for~~distributions of distances from fires to rivers (Figure 4A; k-sample Anderson-Darling test, p<0.~~01~~001) and also to roads (Figure 4B, ~~p<0.01).~~ k-sample Anderson-Darling test, p<0.001). A comparison between Figures 4A and B with their corresponding null-model curves in Figures 4C and D indicates that most fires were much closer to the river and the road networks than a null-model would suggest. In addition to the k-sample Anderson-Darling tests, we computed pairwise comparisons between curves within each of the two sets of CFD in order to evaluate the magnitude of their differences. The results, shown in Tables B1 and B3 in Appendix B, corresponding to comparisons between curves in Figs. 4A and in Fig. 4C respectively, indicate that differences went from 0.01 to 0.39

(average value of 0.2) for distances from fires to rivers (Figs. 4A and Table B1) and from 0.09 to 0.3 (average value of 0.21) for distances from rivers to roads (Figs. 4B and Table B3).

Figure ~~4~~4A shows that ~~most fires were closely associated with the river network, in the case of Ecuador~~ 80% of fires in Ecuador were within 300 m of the closest rivers, ~~500~~whereas for Colombia ~~and within less than~~ this figure increased to 500 m and remained nevertheless below 1 km for the other countries. ~~The case for roads is different since it is really in Brazil where fires were closest to the rivers but within~~Figure 4B, in addition, indicates that a large proportion of distances from fires to roads was below 10 km ~~of the nearest road. It was evident that the~~for all countries. In turn, a comparison between Figs. 4C and 4D also shows that null models for rivers and roads ~~were different~~behaved differently. The CFDs of the null model for rivers (Fig. 4C) showed a strikingly similar set of curves for all five countries, suggesting that distances from fires to rivers were similarly distributed regardless of the country. Although a k-sample Anderson-Darling test of that datasets in Fig. 4C yielded a significant p-value <0.001, the magnitude of the pairwise differences between null-model curves in Fig.4C was very small (0.01-0.08, average value of 0.039; see Table A3, Appendix B) compared to the differences in Fig. 4A (Table B1, Appendix B), corroborating their apparent similarity.).. That is, although the p-value indicates that the effect (i.e. the difference between curves) exists, the magnitude of that difference in this case is very small (Sullivan and Feinn, 2012). On the other hand, a visual inspection of the distribution of null model distances from fires to the closest roads (Fig. 4D) showed noticeable differences between countries ~~(Figures 4 C,D). The null model of the CFDs for rivers was very similar for all countries, illustrating~~, a fact that ~~rivers were similarly distributed independent~~was confirmed by a k-sample Anderson-Darling test (p<0.001) and by the relatively large magnitude of the ~~country. On the contrary the comparison of the null model to the closest roads showed significant~~pairwise differences between ~~countries (Anderson-Darling test, p<0.01). Comparing the~~null-model CFD curves (0.15-0.48, average value of 0.3; see Table B4, Appendix B). A final examination of the curves in Figure ~~4,~~4D points out that the country with the highest road density (~~theroretical~~null-model locations closest to roads) in the Amazon was Ecuador, followed by Peru, Colombia and Brazil. ~~In the Supplementary Information we present a summary of the tests undertaken to compare between countries the observed CFDs to the closest river or road in their respective territory.~~

In relation to the occurrence of fires in the deforestation frontier and where the forest is fragmented, all countries presented a significant relation ~~to~~with the distance to the forest edge (~~Table 2~~Appendix C). There were significant differences between countries of the CFDs of the distance of the active fire detection to the forest edge (~~Supplementary Information 2~~Appendix C), both towards inside the forest (Figure 5 A, Anderson-Darling test, p≤0.01) and outside the forest (Figure 5 B, Anderson-Darling test, ~~-~~p≤0.01). The vast majority of fires ~~occur~~occurred within 500 m outside (Figure 5B) of the forest edge, with Colombia presenting the most fires occurring close to the edge (e.g., 80% within 250 m outside the forest or in the forest).

Discussion

~~Our results indicated the temporal pattern of fire occurrence in NW Amazon tropical forests was determined by its latitudinal position (North/South) and by the country. Thus, intense fires seasons in the Northern Hemisphere were almost opposite to what is expected in the Southern Hemisphere Amazonia in terms of temporal variability (see Figure 1). Fire dynamics is strongly influenced by climate, and indeed the dry season (~July-September) in the southern Amazonia corresponded to a wet season in northern Amazonia and this is a well-established feature. For example, 2004/05, 2006/07, and 2009/10 were years of El Nino during dry season in the Northern Hemisphere, while increased SST in the Atlantic Ocean were responsible for the 2005 and 2010 droughts during dry season in the Southern Hemisphere (Phillips et al., 2009; Saatchi et al., 2013). The Atlantic Multidecadal Oscillation (AMO), for instance, in 2004, 2005, 2007 and 2010 also influenced fire patterns, with strongly positive effects north of the equator (Chen et al., 2011). Despite the intraannual variability, the internannual comparison through the average annual fire density for the time period studied did not differ significantly between north and south. This indicated that north and south of the equator may differ in when fire occurs but not on the intensity and land affected, as the two hemispheres have been equally impacted/affected by fire.~~

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Our results also indicated differences in fire patterns between countries. In 2005, fire density was higher in Brazil in association with increased SST in the Atlantic Ocean; and in particular the state of Acre, was the epicenter of the drought ~~(Aragão et al., 2007; Chen et al., 2011)~~(Aragão et al., 2007; Chen et al., 2011). In the case of the states of Amazonas and Acre, AMO had a stronger positive correlation in 2004, 2007, and 2010 ~~(Chen et al., 2011).~~(Chen et al., 2011). Colombia had higher fire density in 2004 and 2007, two dry seasons associated with El Niño ~~(Armenteras-Pascual et al., 2011)~~(Armenteras-Pascual et al., 2011) and also influenced by the AMO ~~(Chen et al., 2013b).~~(Chen et al., 2013b). For Ecuador, only 2004 and 2005 stood out as the relative higher density years for this country likely associated ~~to~~with the AMO in 2004 and the SST associated 2005 drought. Venezuela, the only country with all its territory in the northern hemisphere for this study, presented a high density of fires in 2004 in association with AMO ~~(Chen et al., 2011)~~(Chen et al., 2011) and in the 2007 El Niño year following the same pattern as Colombia. Finally, in 2005 and 2010 Peru presented high densities of fires as expected being in the southern hemisphere. However, Peru~~,~~ stood out in 2007 (a year with particularly more fires in the Northern Hemisphere) for excessive fire density and another peak in 2012. The first could be associated to the AMO, and for the 2012 the SST or La Niña year (Marengo et al., 2013) but also this might indicate that ~~above~~apart from climate there are other factors influencing the occurrence of fire in this country.

Regarding the influence of accessibility ~~in~~on fire occurrence, we also found (as obtained in a recent study in the legal Amazon, Kumar et al. 2014) that fires were associated to roads, most of them within 10 km but with a lower 75% of the 90% found in the Legal Amazon. This was likely due to the unavailability of data on unmapped and newly developed roads. Unlike the Legal Amazon study, we did not look at the official and unmapped or unofficial roads because this information is not available yet nor is the year by year road development for most ~~north western~~NW Amazonian countries. However, and contrary to ~~this study,~~Kumar et al(2014), we found that fires are also strongly associated to rivers, in particular for Colombia, Venezuela and Peru where most fires occur within 1 km of the closest river. The fact that we ~~obtain~~also obtained this result ~~also~~ in Brazil, where Kumar et al. (2014) did not find this association between fires and rivers, is probably due to the fact that they only accounted for navigable rivers. Our study considered the whole river network given the fact that many colonist in the frontier use small boats to access resources in the forest.

Our results revealed differing relationships between roads, fragmentation and deforestation between countries. The opening of roads in Ecuador and Peru, related to the oil industry ~~(Espinosa et al., 2014; Finer et al., 2015; Finer and Jenkins, 2012; Finer and Orta-Martínez, 2010; Mäki et al., 2001)~~(Espinosa et al., 2014; Finer et al., 2015; Finer and Jenkins, 2012; Finer and Orta-Martínez, 2010; Mäki et al., 2001), might be an explanation for increased fire occurrence and deforestation in these two countries. The ~~departments~~sub regions where some of these developments have occurred have also reported the highest forest loss, particularly in 2009 and 2010 ~~(Potapov et al., 2014)~~(Potapov et al., 2014). Colombia contains a large area of the undeveloped Amazon and fire is used as a tool to open the colonization frontier. Fire is also used as a pasture management tool once the frontier advances and basic road infrastructures are developed (Armenteras and others 2013; Dávalos and others 2014). In Venezuela, although not included in the study due to the poor quality road data, detected fires most likely resulted from expansion of the agricultural frontier (Pacheco et al., 2014).

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~~Despite the fact that forest is associated with fire (Cochrane 2003), there was little evidence outside Brazilian Amazon of fire as an edge effect at large scales (Cochrane & Laurance 2002). Our results showed that in this part of the Amazon, most fires occurred close to the edge and as such, fire occurrence was strongly linked in all countries to forest fragmentation. The distance to which fire edge effects were detected in our study (within 2 km of forest interior edge) coincided with previously recorded distances of fire influence of at least 2-3 km in other areas of the Amazon (Armenteras et al., 2013a; Cochrane and Laurance, 2002) or with the 1-2.7 km at which edge desiccating effects penetrated into fragmented forests (Briant et al., 2010). Our results also aligned with other studies in Brazil and Colombia concluding fire frequency increases at the forest edge (Cochrane 2001; Cochrane and Laurance 2002; Armenteras and others 2013). The distance of fire to forest edge in our study (within 2 km of the edge either inside or~~

outside the forest) coincided with previously reported distances of fire influence of at least 2-3 km in other areas of the Amazon (Cochrane and Laurance 2002; Armenteras and others 2013). Some studies argue the majority of fires in Brazil are agricultural fires or escaped fires from managed pastures (Cano-crespo et al., 2015). It is likely that the countries with a higher percentage of fires resulting in deforestation are those countries, such as Colombia, that have most fires closest to the forest edge and less agricultural development (Armenteras and others 2013). Nevertheless, whether a forest fire is an unintended escaped fire or a fire used for forest conversion to other land use, the strong association of fires with both accessibility and fragmentation is an important result worth highlighting for the different countries. Indeed, if burning mostly occurs along forest edges and is also associated to increased access to the forest, all tropical forest edges in all countries are becoming increasingly more exposed to further disturbances. As such there might be different levels of impacts and different causes but there are common ecological consequences as an increased desiccation affecting forest structure and composition, degrading these forests, decreasing living biomass and finally reducing their capacity to act as a carbon sink (Balch et al., 2015; Harper et al., 2005).

Conclusions

This study showed that, within the same tropical forest biome, there were clear differences between countries in terms of timing of peak fire season (different years, different peaks per country) and that accessibility was associated with increased fires.Despite the fact that forest is associated with fire (Cochrane 2003), there was little evidence outside Brazilian Amazon of fire as an edge effect at large scales (Cochrane & Laurance 2002). Our results showed that in this part of the Amazon, most fires occurred close to the edge and as such, fire occurrence was strongly linked in all countries to forest fragmentation. The distance to which fire edge effects were detected in our study (within 2 km of forest interior edge) coincided with previously recorded distances of fire influence of at least 2-3 km in other areas of the Amazon (Armenteras et al., 2013a; Cochrane and Laurance, 2002) or with the 1-2.7 km at which edge desiccating effects penetrated into fragmented forests (Briant et al., 2010). Our results also aligned with other studies in Brazil and Colombia concluding fire frequency increases at the forest edge (Cochrane 2001; Cochrane and Laurance 2002; Armenteras et al., 2013). Some studies argue the majority of fires in Brazil are agricultural fires or escaped fires from managed pastures (Cano-crespo et al., 2015). It is likely that the countries with a higher percentage of fires resulting in deforestation are those countries, such as Colombia, that have most fires closest to the forest edge and less agricultural development (Armenteras and others 2013). Nevertheless, whether a forest fire is an unintended escaped fire or a fire used for forest conversion to other land use, the strong association of fires with both accessibility and fragmentation is an important result worth highlighting for the different countries. Indeed, if burning mostly occurs along forest edges and is also associated to increased access to the forest, all tropical forest edges in all countries are becoming increasingly more exposed to further disturbances. As such there might be different levels of impacts and different causes but there are common ecological consequences as an increased desiccation affecting forest structure and composition, degrading these forests, decreasing living biomass and finally reducing their capacity to act as a carbon sink (Balch et al., 2015; Harper et al., 2005).

Conclusions

This study showed that, within the same tropical forest biome, there were clear differences between countries in terms of timing of peak fire season (different years, different peaks per country) and that accessibility was associated with increased fire occurrence. Forest edge effects occurred equally in all countries and might be worthwhile addressing them either regionally or within each individual country since they are causing forest degradation. All our results underscored the influence not only of climate but likely the more strongly socio-economic factors (van der Werf et al., 2004)(van der Werf et al., 2004) in increasing fires driving deforestation. Future management plans for NW Amazonia should consider the potential and synergistic edge effects derived from infrastructure development plans and national climate adaptation and mitigation policies. More frequent fires along increasingly fragmented forests may also have other undesired cascade effects in terms of forest degradation and emissions. Subsequent forest loss should be addressed in the context of REDDReducing Emissions from Deforestation and Forest Degradation (REDD) strategies or other policy mechanisms implemented locally.

Author Contributions

DA and JR conceived the idea, designed the analysis and performed data analysis and wrote the manuscript; JSB and RM analyzedanalysed the data. KT contributed to writing part of the manuscript. All authors contributed to revising the manuscript.

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Figures

Figure 1. Location of the study area, roads and river network and fire hotspots detected for the period 2003-2015 and portion of the territory shared amongst countries.

Figure 2. Interannual variability of satellite detected active fires density (Number/ 1000sqkm) per latitudinal position (North, South)() (A) and country (B).

Figure 3. Monthly average satellite detected active fires density (Number/ 1000sqkm) per latitudinal position (North, South)() (A) and country (B).

Figure 4. Cumulative frequency of the observed closest distance of fires to rivers (A) and roads (B) for each country and of the null model for distances to rivers (C) and roads (D) for each country.

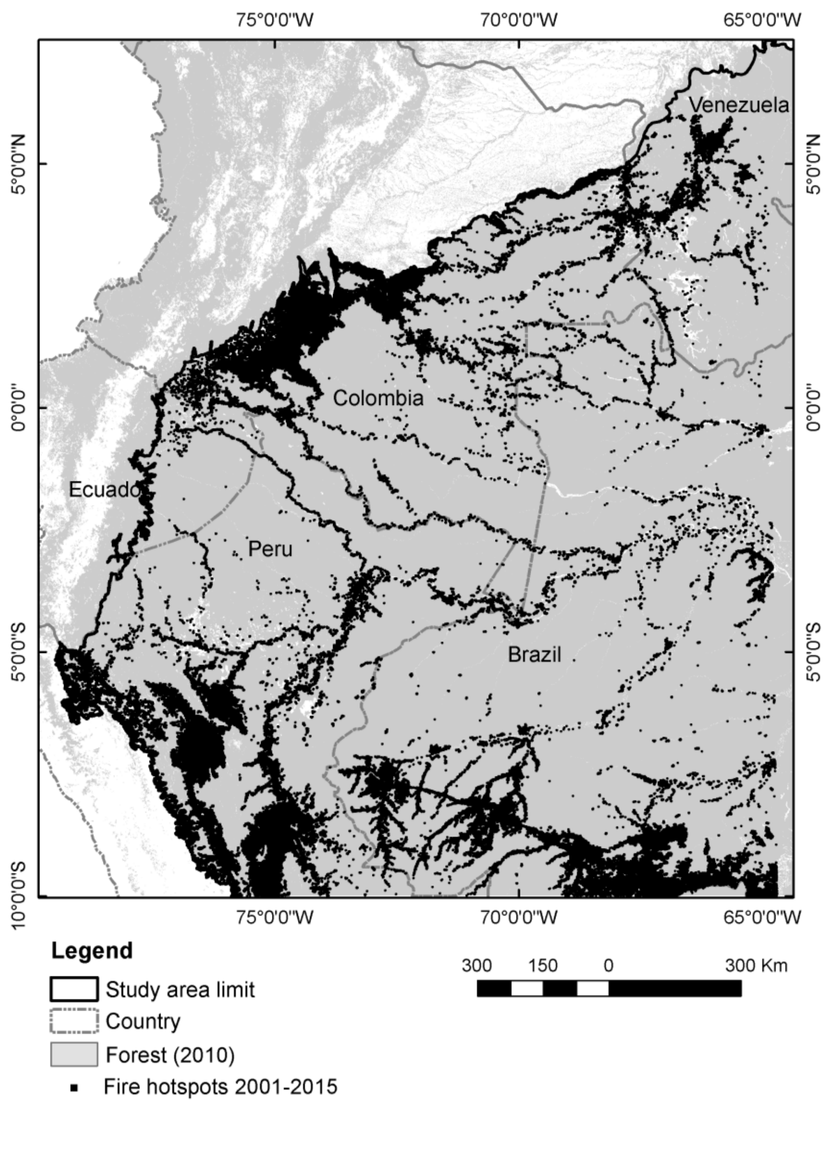
Figure 5. Cumulative frequency of the observed closest distance of fires occurring outside (A) and inside the forest (B) to the forest edge in 2010 for each country.

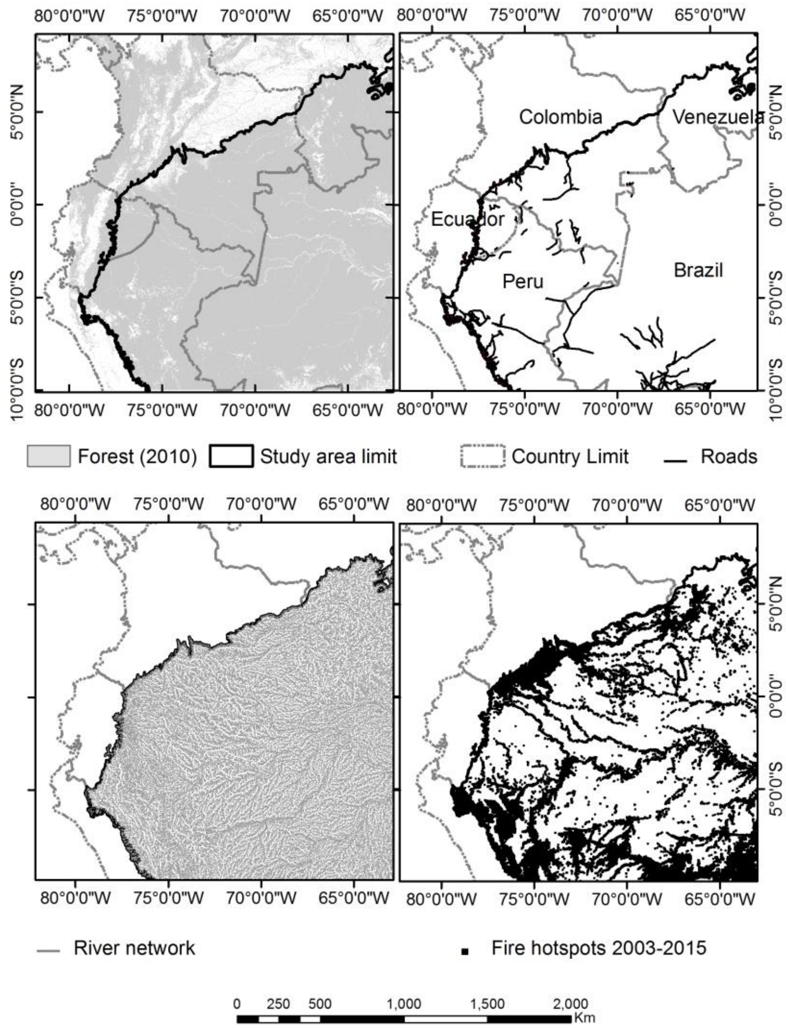
Tables

Table 1 Results of the Kolmogorov-Smirnov tests between the observed and the null model for distances of fire occurrences to roads and rivers in each country.

Table 2. Results of the Kolmogorov-Smirnov tests between the observed and the null model for distances of fire occurrence to forest edge (outside or inside the forest) in each country.

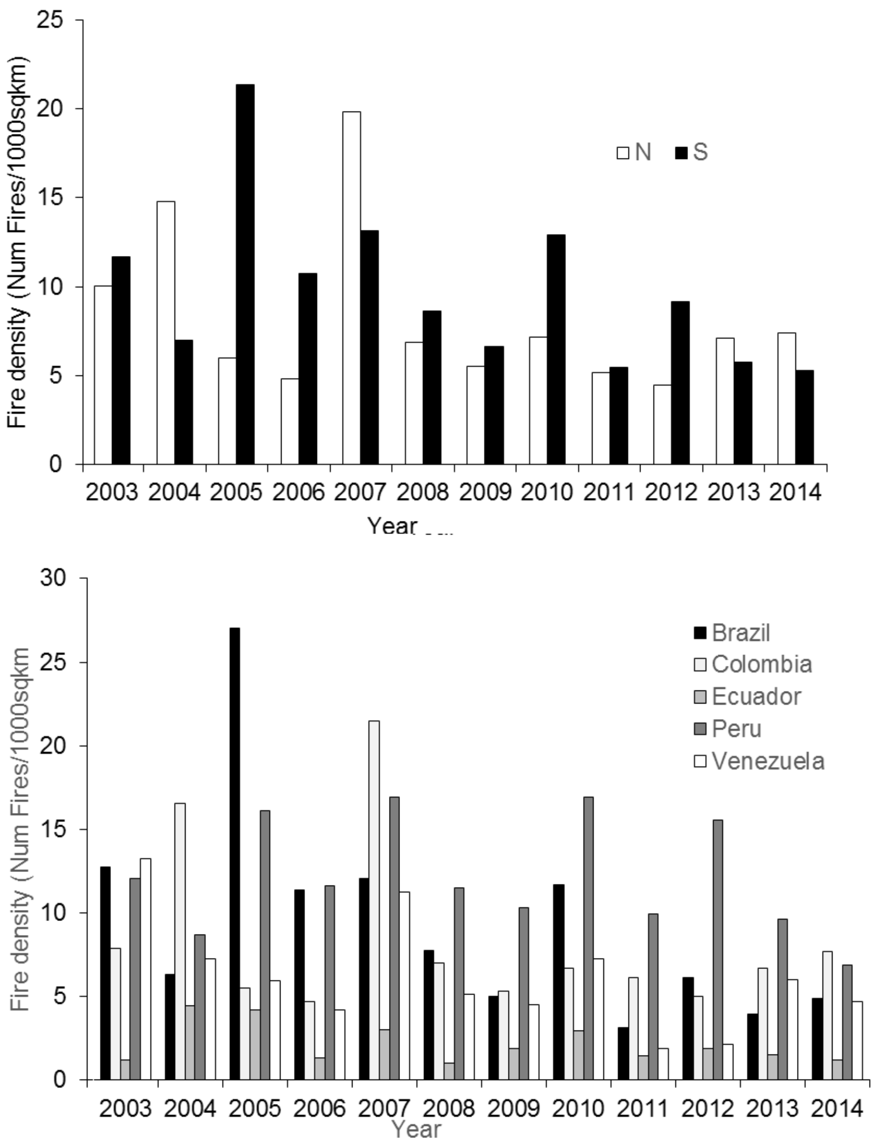
Figure 1. Location of the study area, roads and river network and fire hotspots detected for the period 2003-2015 and portion of the territory shared amongst countries.

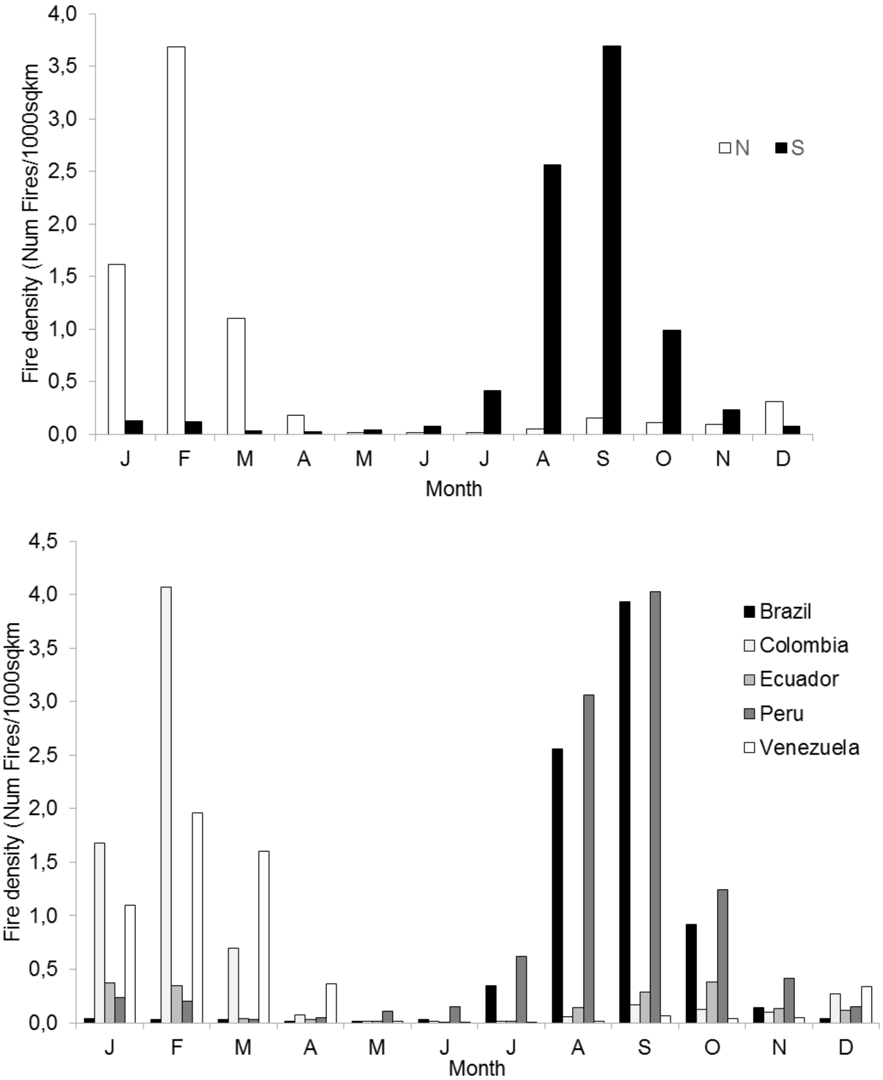




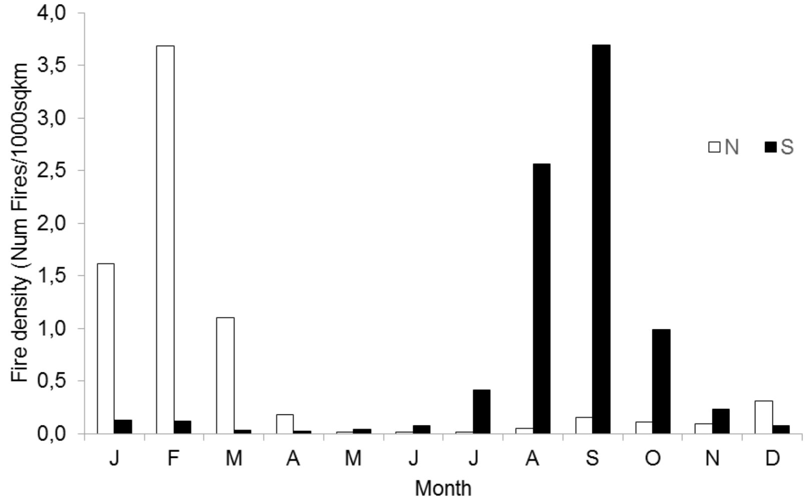
80°0'0"W
75°0'0"W
70°0'0"W
65°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
Colombia
Venezuela
Ecuador
Peru
Brazil
Forest (2010)
Study area limit
Country Limit
Roads
River network
Fire hotspots 2003-2015
0 250 500 1,000 1,500 2,000
Km

Figure 2. Interannual variability of satellite detected active fires density (Number/ 1000sqkm) per latitudinal position (North, South)(A) and country (B).




Fire density (Num Fires/1000sqkm
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
N
S
J F M A M J J A S O N D
Month
Fire density (Num Fires/1000sqkm
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
Brazil
Colombia
Ecuador
Peru
Venezuela
J F M A M J J A S O N D
Month

395 Figure 3. Monthly average satellite detected active fires density (Number/ 1000sqkm) per latitudinal position (North, South)(A) and country (B).



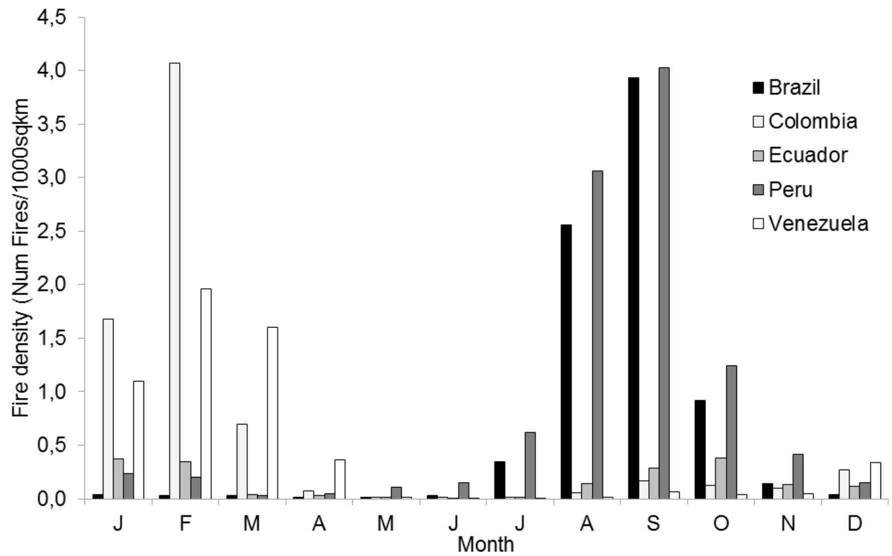


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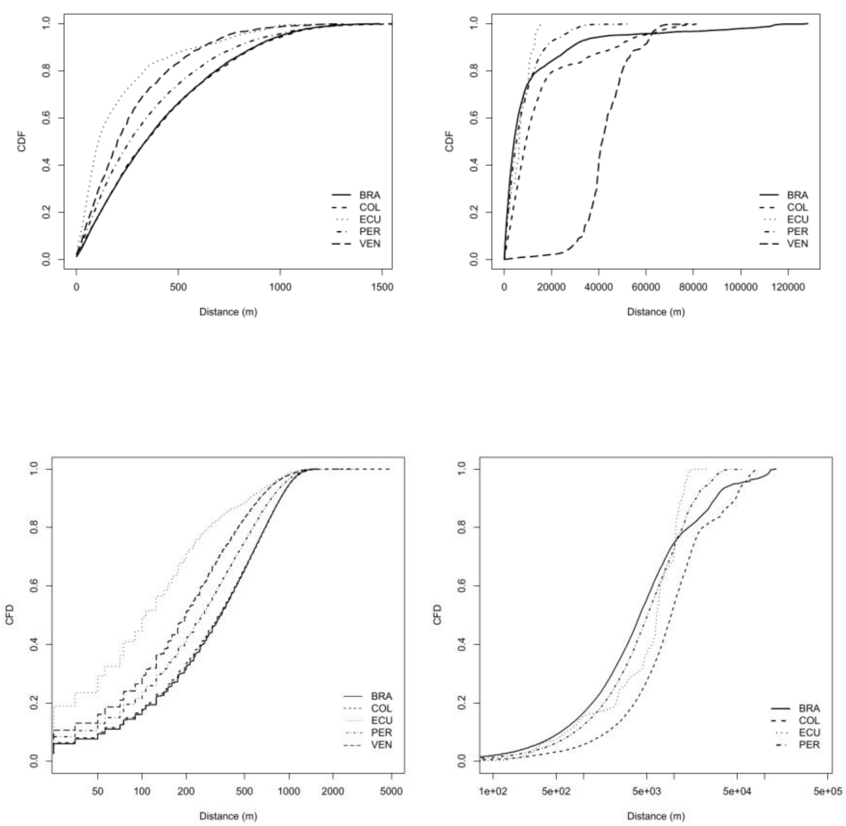
Figure 4. Cumulative frequency of the observed closest distance of fires to rivers (A) and roads (B) for each country and of the null model for distances to rivers (C) and roads (D) for each country. (x ayis is shown in log transform).

A B



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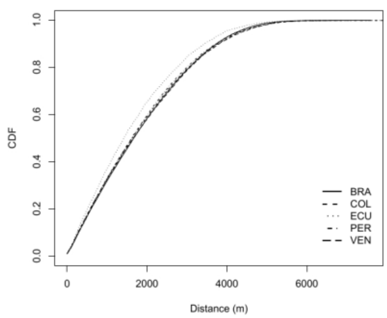
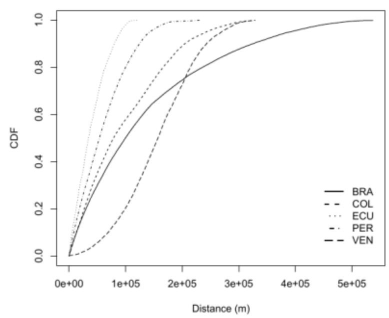
C D


CDF
Distance (m)
BRA
COL
ECU
PER
VEN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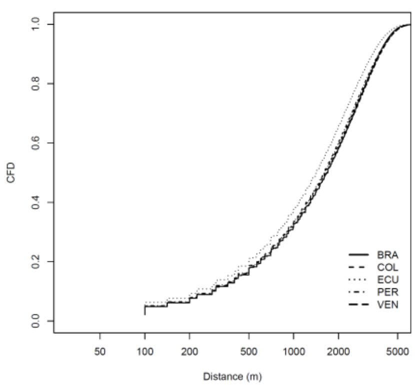
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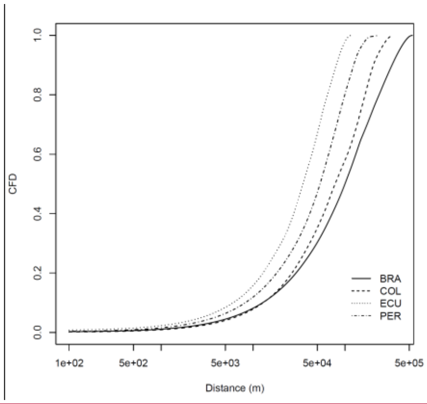
CFD
Distance (m)
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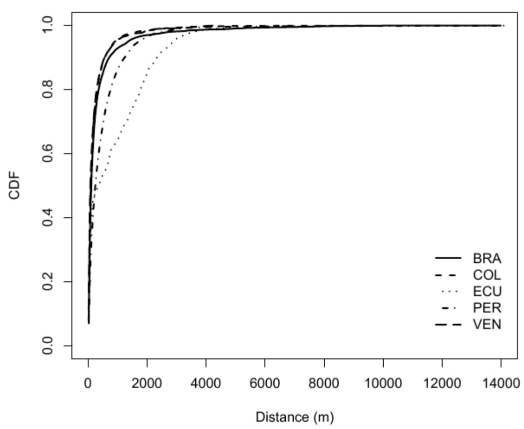
Figure 5. Cumulative frequency of the observed closest distance of fires occurring outside (A) and inside the forest (B) to the forest edge in 2010 for each country.



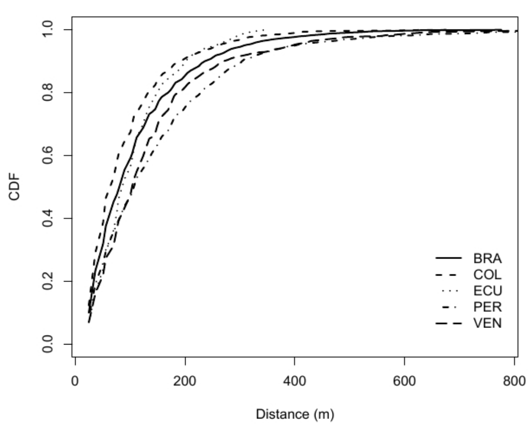
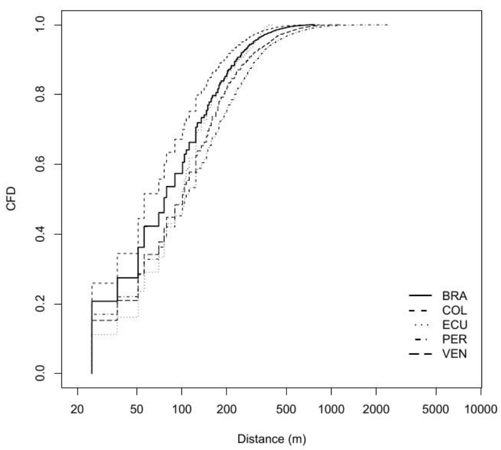


Table 1 Results of the Kolmogorov-Smirnov tests between the observed and the null model for distances of fire occurrences to roads and rivers in each country.



CFD
1.0
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0.6
0.4
0.2
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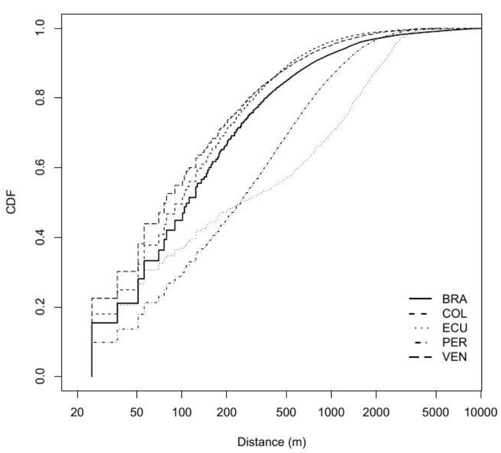
ECU
PER
VEN
20
50
100
200
500
1000
2000
5000
10000
Distance (m)



CDF
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Distance (m)

~~Country~~	~~Accessibility~~	~~D-statistics~~	~~p-value~~
~~Brazil~~	~~rivers~~	~~0.633~~	~~< 0.01~~
~~Brazil~~	~~roads~~	~~0.706~~	~~< 0.01~~
~~Colombia~~	~~rivers~~	~~0.620~~	~~< 0.01~~
~~Colombia~~	~~roads~~	~~0.644~~	~~< 0.01~~
~~Ecuador~~	~~rivers~~	~~0.706~~	~~< 0.01~~
~~Ecuador~~	~~roads~~	~~0.768~~	~~< 0.01~~
~~Peru~~	~~rivers~~	~~0.651~~	~~< 0.01~~
~~Peru~~	~~roads~~	~~0.713~~	~~< 0.01~~
~~Venezuela~~	~~rivers~~	~~0.702~~	~~< 0.01~~

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Table 2. Results of the Kolmogorov Smirnov tests between the observed and the null model for distances of fire occurrence to forest edge (outside or inside the forest) in each country.

Country	Forest edge	D-statistics	p-value
Brazil	outside the forest	0.969	< 0.01
Brazil	inside the forest	0.801	< 0.01
Colombia	outside the forest	0.938	< 0.01
Colombia	inside the forest	0.768	< 0.01
Ecuador	outside the forest	0.978	< 0.01
Ecuador	inside the forest	0.705	< 0.01
Peru	outside the forest	0.940	< 0.01
Peru	inside the forest	0.687	< 0.01
Venezuela	outside the forest	0.927	< 0.01
Venezuela	inside the forest	0.737	< 0.01

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