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# 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 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 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 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 also found difference in peak fire occurrence by country with fire peak in Colombia and Venezuela in February; peak fire in September for Brazil and Peru; and Ecuador presented two fire peaks. 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. 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 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 what 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; Fearnside and Barbosa, 2004; 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 and enabled conditions related to increased accessibility to forests (Barber et al., 2014; Laurance et al., 2002) and changing climatic patterns (Aragão et al., 2008; Flannigan et al., 2009; Malhi et al., 2008).

Fire occurrence in the tropics has a particular pattern: in Latin America it has been established that, in general terms, 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 (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 addition to the cyclical severe fire seasons associated with climatic oscillations and climate change, fires in the Amazon occur more frequently in previously fragmented forests and are largely associated with deforestation and forest edges (Cochrane & Laurance 2002; Cochrane 2001).

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) that contribute to global warming. Fires also cause a reduction in above ground biomass (Cochrane and Schulze, 1999; Kauffman and Uhl, 1990), primary production (Kinnaird and O'Brien, 1998), loss of biodiversity, and disruption of regional water and energy cycles (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).

Throughout the tropics, road development increases the susceptibility of forests to deforestation and forest fragmentation by exposing forest edges to increasing levels of disturbances (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). Much less is known regarding factors influencing fire dynamics and patterns in NW Amazon, nor linking fires to deforestation and fragmentation in the Ecuador, Peruvian, Colombian and Venezuelan parts of the Amazon (but see 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). In this study we analyzed the dynamics and patterns of fires in the most northwestern part of the Amazon basin to highlight regional differences in patterns of fire occurrence in relation to accessibility and forest fragmentation between neighboring 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?

**Methods**

**Study site**

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The study area (Figure 1) corresponded to the northwestern (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). 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. (Shimada et al., 2014).
- For fire data we used the satellite active fire datasets from both MODIS 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 5.1). We only used data with confidence levels over 30% (medium 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 used the best available information for the region on roads from CIESIN (Center for International Earth Science Information Network, Columbia University and of Georgia, 2013). This database shows no roads for Venezuela in the Amazonia, therefore, we removed Venezuela from the analysis of accessibility by roads.
- We used the USGS HydroSheds data for the river network (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 and interannual variability. We tested for differences in fire occurrence between those occurring north and south of the Equator using paired two sample t tests and among countries by means of ANOVA tests to detect the effect of its latitudinal position and the country.

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 fire hotspots to the closest river and road. 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 of theoretical distances to the explanatory road and river networks by creating a regularly spaced geographic grid of 1 km apart locations (2,254,046 points) across the study area of Colombia, Peru, Ecuador, Venezuela, and Brazil) following the approach presented by Kumar et al (2014). We called this model the null model of distances to roads and rivers, against which fire distance distributions are compared. For the sake of comparison with the work of Kumar et al. (2014), the non parametric Kolmogorov-Smirnov test was applied to test for differences in the CFDs for both the active fire distances and the null model for each country, with values varying from zero (no significant differences between two distributions) to one (two distributions totally different indicating fires occurring associated to the explanatory variables).

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 to the forest edge (inside or 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 in 2012 whilst the 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 (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 fire density was significantly different between countries (Figure 2B, ANOVA F=8.0, p<0.01).

Seasonal differences between the northern and 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 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 results of the Kolmogorov-Smirnov tests 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).

On the other hand, Figure 4 shows the comparison between countries of the CFDs of the observed distances of fire to the closest river and roads. There are also significant differences between countries for distances to rivers (Figure 4A; Anderson-Darling test, p<0.01) and also to roads (Figure 4B, p<0.01). Figure 4 shows that most fires were closely associated with the river network, in the case of Ecuador 80% of fires were within 300 m of the closest rivers, 500 for

Colombia and within less than 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 10 km of the nearest road. It was evident that the null models for rivers and roads were different between countries (Figures 4 C,D). The null model of the CFDs for rivers was very similar for all countries, illustrating that rivers were similarly distributed independent of the country. On the contrary the comparison of the null model to the closest roads showed significant differences between countries (Anderson-Darling test, $p<0.01$). Comparing the curves in Figure 4, the country with the highest road density (theroretical 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 the distance to the forest edge (Table 2). There were significant differences between countries of the CFDs of the distance of the active fire detection to the forest edge (Supplementary Information 2), both towards inside the forest (Figure 5 A, Anderson-Darling test, $p\leq0.01$) and outside the forest (Figure 5 B, Anderson-Darling test, $p\leq0.01$). The vast majority of fires occur 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.

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). 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). Colombia had higher fire density in 2004 and 2007, two dry seasons associated with El Niño (Armenteras-Pascual et al., 2011) and also influenced by the AMO (Chen et al., 2013b). For Ecuador, only 2004 and 2005 stood out as the relative higher density years for this country likely associated to 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) 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 Niña year (Marengo et al., 2013) but also this might indicate that above climate there are other factors influencing the occurrence of fire in this country.

Regarding the influence of accessibility in 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 Amazonian countries. However and contrary to this study, 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 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), might be an explanation for increased fire occurrence and deforestation in these two countries. The departments where some of these developments have occurred have also reported the highest forest loss, particularly in 2009 and 2010 (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).

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. 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 more strongly socio-economic factors (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 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 analyzed 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, 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.

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**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.

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

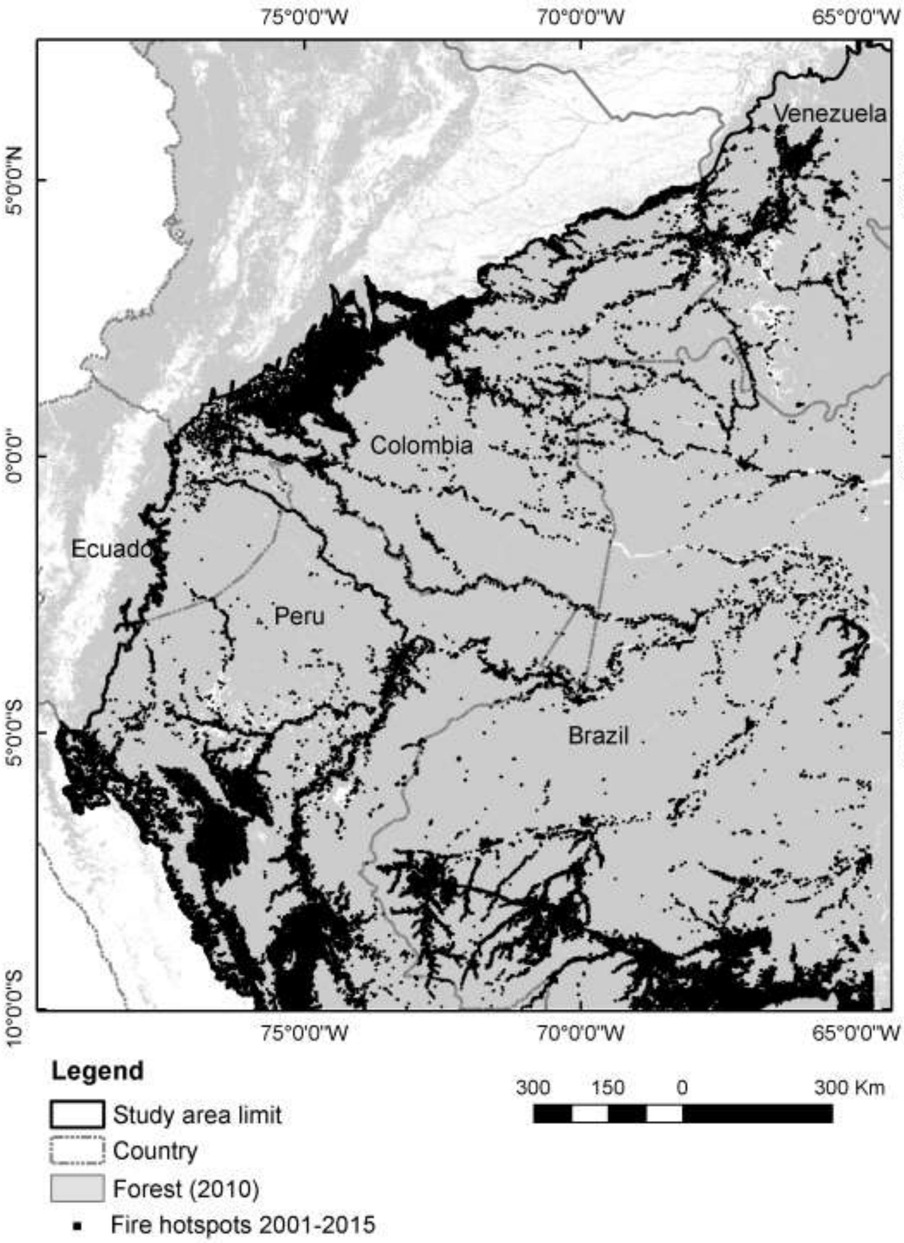


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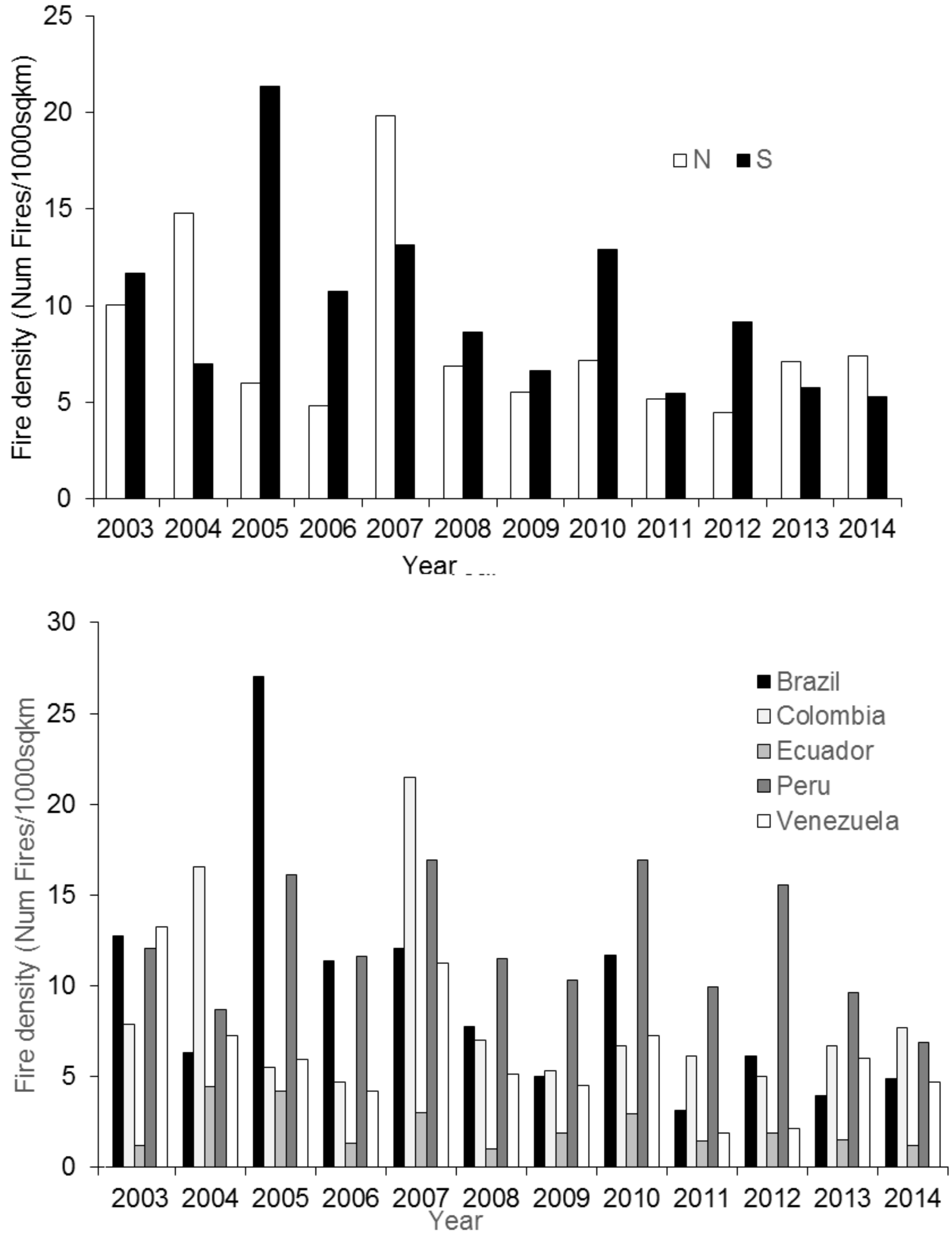
Figure 2. Interannual variability of satellite detected active fires density (Number/ 1000sqkm) per latitudinal position (North, South)(A) and country (B).



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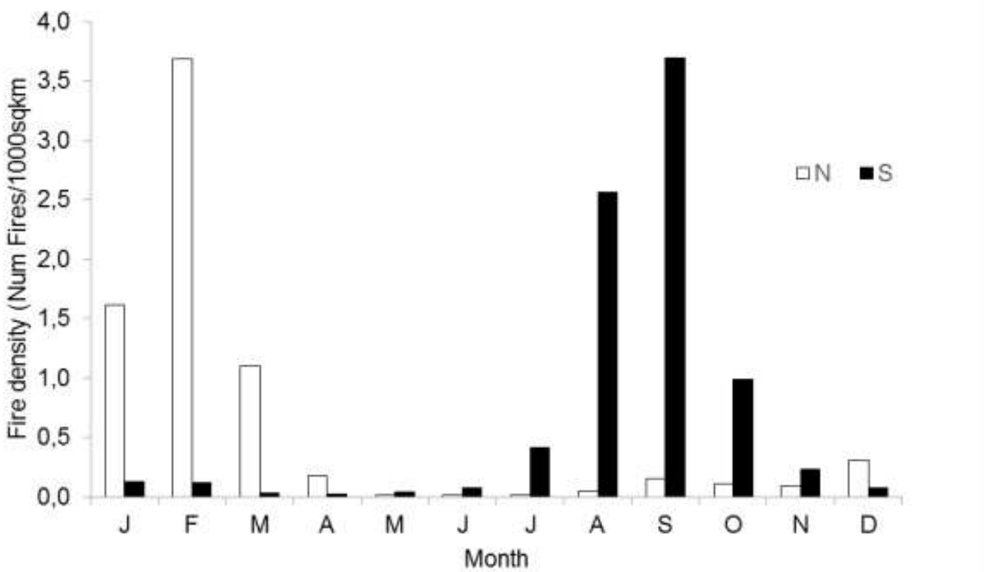


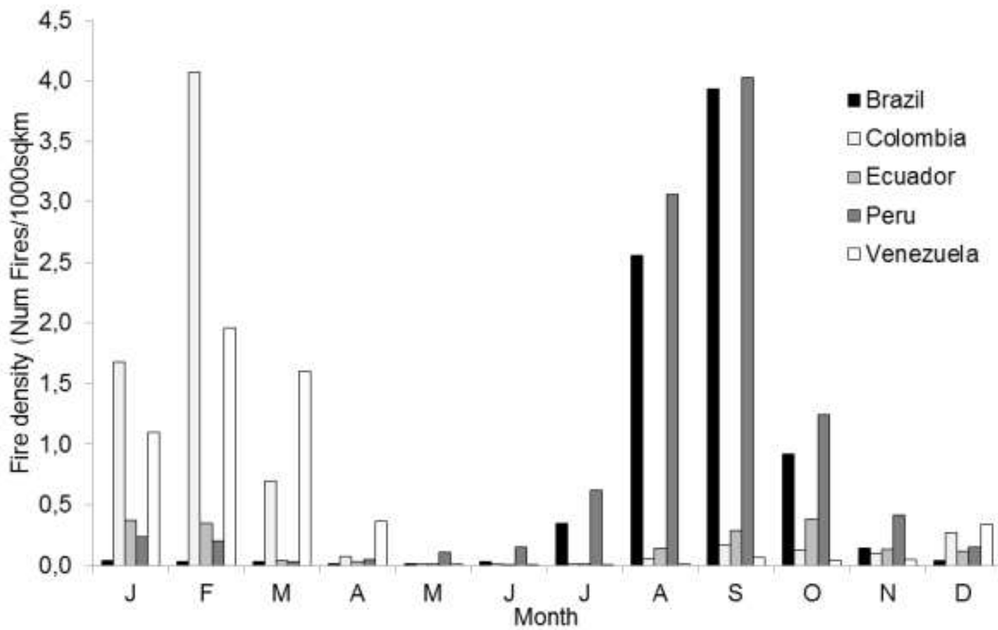


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Figure 3. Monthly average satellite detected active fires density (Number/ 1000sqkm) per latitudinal position (North, South)(A) and country (B).

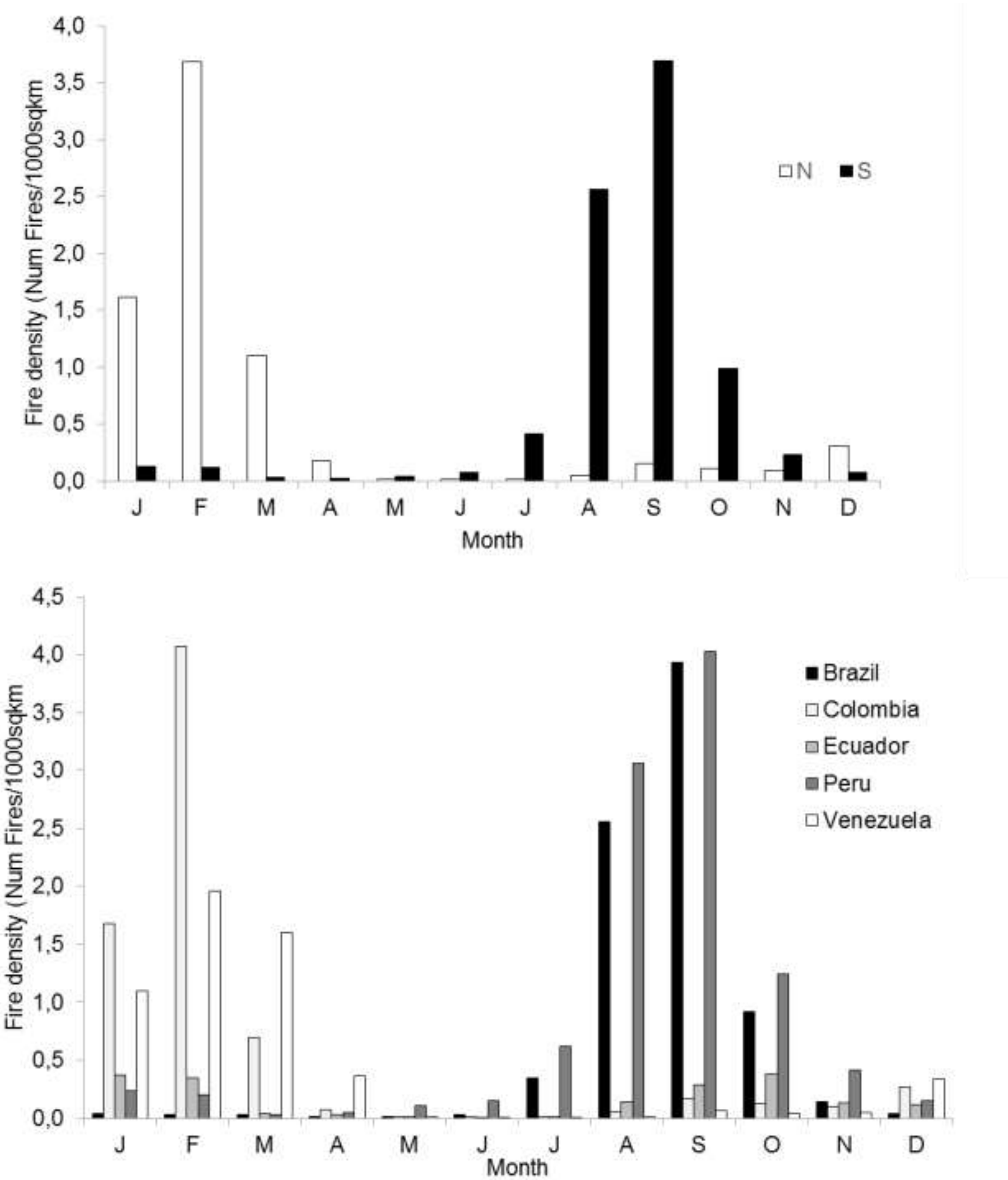

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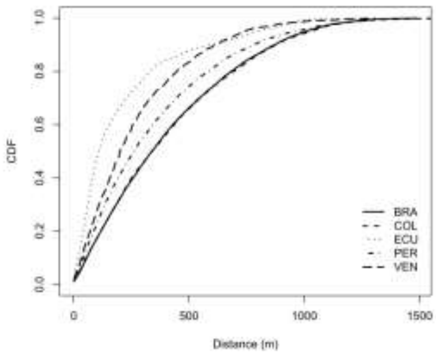
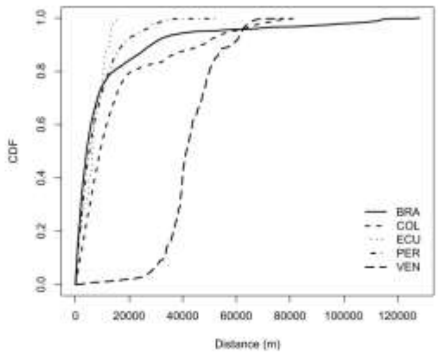
Figure 4. Cumulative frequency of the observed closest distance of fires to rivers (A) and roads (B) for each country and of the null model for distances to rivers (C) and roads (D) for each country.

A




B

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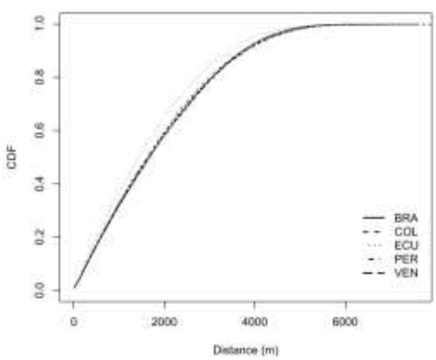
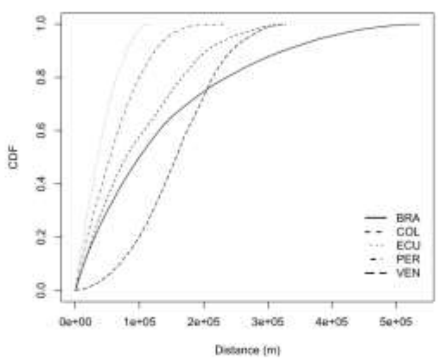



D



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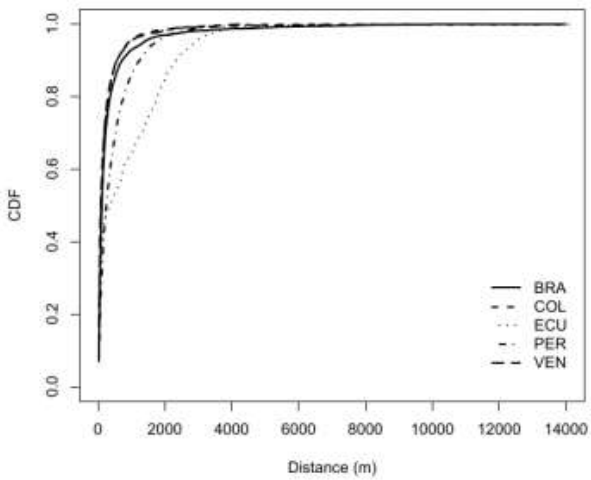
319 Figure 5. Cumulative frequency of the observed closest distance of fires occurring outside (A) and inside the forest
320 (B) to the forest edge in 2010 for each country.

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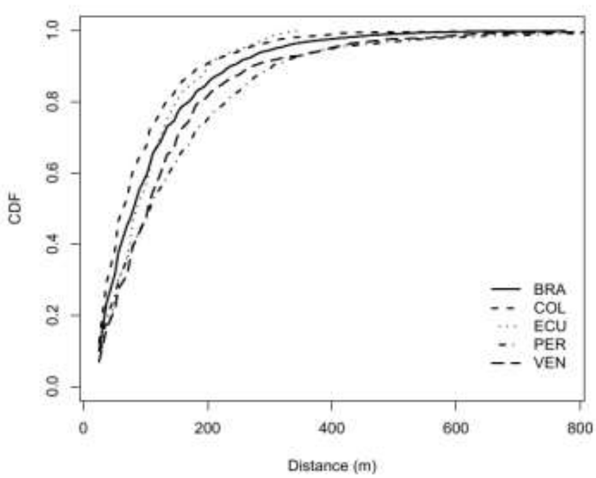


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**Table 1** Results of the Kolmogorov-Smirnov tests between the observed and the null model for distances of fire occurrences to roads and rivers in each country.

| 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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