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Ingeniería en Geociencias

Influencia de la rugosidad del terreno en los incendios forestales

Stalin Mauricio Guamán Moromenacho

3 de mayo de 2021, ciudad de Tena, Napo, Ecuador.

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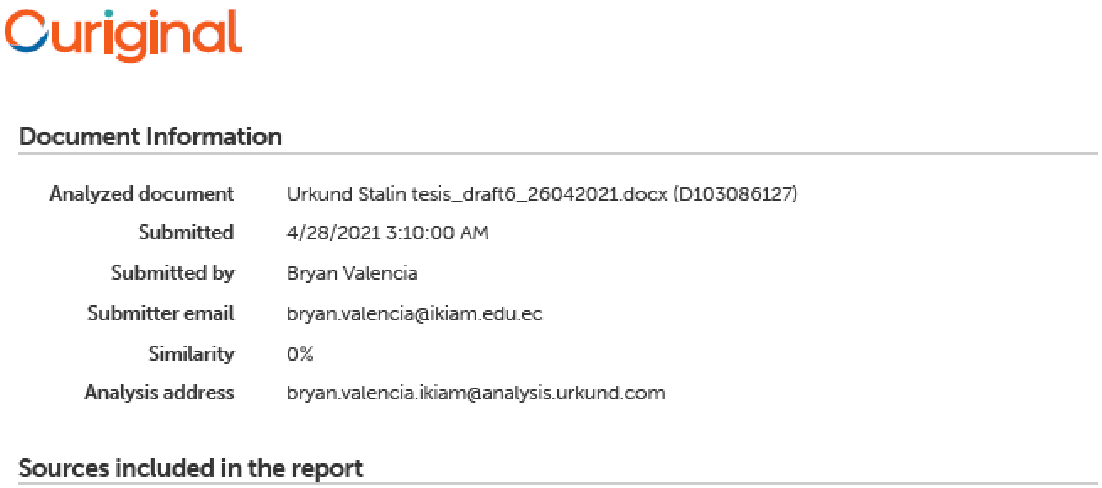

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Stalin Guamán

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RESUMEN

Objetivo: Comprobar la hipótesis de que la rugosidad del terreno influye en los regímenes de incendios de dos maneras (i) valores altos de rugosidad funcionan como barreras naturales que evitan la propagación de los incendios y (ii) el fuego no es una característica aleatoria en el paisaje.

Ubicación: Siete sitios en la cordillera de los Andes tropicales entre 2°77' y 13°60' de latitud.

Métodos: Se utilizaron modelos de elevación digital, imágenes satelitales y datos de incendios para analizar las relaciones entre incendios y la rugosidad del terreno en cada sitio de estudio. Examinamos la ocurrencia de incendios como una relación entre el Normalized Difference Vegetation Index (NDVI) y el Índice de Rugosidad del Terreno (TRI). Además, analizamos la distribución de los incendios basados en las características del TRI: áreas donde hubo fuego ($\mathrm{TRI}_{\mathrm{fire}}$), donde no hubo fuego ($\mathrm{TRI}_{\mathrm{nofire}}$), y todo el sitio ($\mathrm{TRI}_{\mathrm{total}}$).

Resultados: (i) La vegetación aumenta consistentemente con el TRI. Las regiones analizadas mostraron que, terrenos rugosos son más propensos a retener la vegetación que los terrenos planos. (ii) La ocurrencia de incendios no es un proceso aleatorio, ya que encontramos diferencias significativas entre $\mathrm{TRI}_{\mathrm{fire}}$, $\mathrm{TRI}_{\mathrm{nofire}}$ y $\mathrm{TRI}_{\mathrm{total}}$ (p-value <= 2.2e-16). $\mathrm{TRI}_{\mathrm{fire}}$.

Conclusiones principales: La rugosidad del terreno influye en la dinámica de los incendios, ya que controla su ocurrencia y modula cómo se propagan en el paisaje. Zonas de alta rugosidad son más propensas a regenerar la vegetación después de los incendios. En el contexto del cambio climático, las regiones con alto TRI podrían funcionar como refugios para la biota.

Palabras claves: Incendios, Rugosidad del Terreno, Trópicos, Cordillera de los Andes, Cambio Climático, Sequías.

ABSTRACT

Aim: The aim was to test the hypothesis that terrain roughness influences fire regimes in two ways (i) high terrain roughness values function as natural barriers that prevent the spread of fires and (ii) fire cannot be a random feature in the landscape.

Location: Seven sites in the tropical Andes Mountain range, between 2° 77' and 13° 60' of latitude.

Methods: We used a digital elevation model, satellite imagery, and fire data sets, to analyze the relationships between fires and terrain roughness. We examined the fire occurrence as a relationship between Normalized Difference Vegetation Index (NDVI) and Terrain Roughness Index (TRI). Also, we analyzed the distribution of fires based on the TRI characteristics: areas where fire occurred (TRI_{fire}), where fire was absent ($TRI_{no\ fire}$), and the entire site (TRI_{total}).

Results: We found that (i) vegetation consistently increases with TRI (R^2=0.8, P=0.0064). The analyzed regions showed that rugged terrains are more capable to retain vegetation than flat terrains. (ii) Fire occurrence is not a random process, as we found significant differences between TRI_{fire}, $TRI_{no\ fire}$, and TRI_{total} (p-value <= 2.2e-16). TRI_{fire} showed a marked range of TRI values (10-20).

Main conclusions: Our analysis demonstrates that terrain roughness influence fire dynamics as it controls their occurrence and modulates how they propagate in the landscape. Areas with high terrain roughness are more likely to regenerate vegetation after fires. In the climate change context, high TRI regions could work as refugia for both, vegetation, and animals.

Keywords: Fires, Terrain Roughness, Tropics, Andean Mountains, Climate Change, Droughts

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Terrain roughness regulates fire occurrence in the tropics

Stalin Guamán[1] & Bryan Valencia[1]

[1]Facultad de Ciencias de la Tierra y Agua, Universidad Regional Amazónica Ikiam, Km 7, Vía Muyuna, Tena, Napo, Ecuador.

Keywords: Fires, Terrain Roughness, Tropics, Andean Mountains, Climate Change, Droughts

Introduction

Wildfires are a worldwide phenomenon that influences atmospheric and terrestrial systems. Fires have a big impact on the environment, shaping the distribution of ecosystems, the geochemical cycles of carbon and phosphorus, and modulating climate (Bowman et al., 2009). Fires also have a direct impact on humans, causing respiratory diseases, economic problems, and destruction of property (Lohman, Bickford, & Sodhi, 2007). Socio-economic studies revealed that burned areas in developing countries are significantly larger than in developed countries. Limited resources linked to small gross domestic products contribute to the inability to implement programs for fire management that would prevent widespread fire events (Aldersley, Murray, & Cornell, 2011). Tropical regions are especially threatened by fire. The largest fires occurred recorded over the last decade were observed in the tropics that also holds the largest number of annual occurrences in comparison to other regions (Cochrane, 2009). Due to ongoing temperature rise and the recurrence of droughts, the frequency and intensity of fire events have increased (Bowman et al., 2011).

In South America, wildfires become enhanced because of the effects of El Niño-Southern Oscillation (ENSO) or the warming of the north Atlantic (Jolly et al., 2015). During the positive phase of ENSO, the total burned area increases in 30% within South America compared to non-ENSO years (Van Der Werf et al., 2004). Also, during the warming of the north Atlantic Sea surface, the Intertropical Convergence Zone (ITCZ) moves northward and induce droughts in this region. During the dry season, between June to September, the region shows a clear reduction in precipitation and humidity, leading to an increase in fires. (José A. Marengo et al., 2008; Jose A. Marengo, Tomasella, Alves, Soares, & Rodriguez, 2011; Zeng et al., 2008). Thus, projected climate scenarios suggest that fires will become more prevalent in the following decades, as droughts become ubiquitous due to climate change, especially in the tropics (European Environmental Agency, 2012; Jolly et al., 2015; Stephens et al., 2013; Urrutia & Vuille, 2009).

The occurrence of fires accelerates the forest loss changing to grasslands, at the same time, grasslands are more prone to be burned. Thus, recurrent fire events will further contribute to the land-use change, allowing the replacement of forest with fire-prone savanna species that may enhance the forest edge effect (Anadón, Sala, & Maestre, 2014; Beerling & Osborne, 2006). These changes are widespread across Amazonian ecosystems; however, the effects are more evident in transition zones between forests and savannas where the contraction of the forest ecosystem is observed (Anadón et al., 2014). Although most of the fire predictions agree that fires will become prevalent, due to the complexity of fire regimes is difficult to determine where the most vulnerable areas are (Williams & Abatzoglou, 2016).

Even though there are several studies in which fires are related to environmental and social variables, very few associate fires with topographic variables (i.e. slope, altitude) (Dissing & Verbyla, 2003; Kushla & Ripple, 1997). Topography can substantially modulate meteorological variables that regulate fire events such as air temperature, precipitation, wind, and evapotranspiration (Dobrowski, 2011). Therefore, understanding the effect that topography has on fires should improve our understanding of fire dynamics, then it will improve predictions of where fires can occur. However, the influence of terrain roughness on fires is still unclear. For instance, Kushla and Ripple (1997) analyzed the correlation between terrain roughness and fire occurrence. The study found no correlation between these variables. However, the analysis was based on Pearson correlation that cannot establish a direct causation. Palaeoecological studies revealed that paleo-fires in the tropical Andes were more common in basins with low terrain roughness than basins with high roughness (Valencia et al., 2016). During fire events, vegetation cover was more persistent in basins with high roughness because uneven terrain act as firebreaks. However, there are no studies that prove if contemporary landscapes have similar behavior. The aim of this study is to evaluate rugosity terrain models with contemporary fire occurrence and vegetation persistence.

We hypothesize (i) that the high terrain roughness values function as natural barriers that prevent the spread of fires. Therefore, areas with high Terrain Roughness Index (TRI; *sensu* Valencia et al., 2016) should have larger areas covered with forests than areas with low TRI. A second hypothesis is related to the randomness of fire events. (ii) Fires cannot be a random feature in the landscape. Therefore, the TRI distribution of burned areas (TRI_{fire}) should differ from the TRI distribution of non-burned areas ($TRI_{no\ fire}$) and the distribution of all TRI (TRI_{total}) in a site. This study, makes use of a digital elevation model, satellite imagery, and fire data sets, to analyze the relationships between fires and terrain roughness. Our analysis will allow the classification of the landscape based on its fire vulnerability.

Study Area

The study area is located along the tropical Andes Mountain range, between 2°77’ and 13°60’ of latitude. The analysis was focused on seven sites, two in Ecuador (Chorreras and Surucucho) and five in Peru (Chochos, Huanmanmarca, Refugio, Pacucha, and Caserococha; see figure 1 and table 1). The sites were selected to test fire dynamics in modern landscapes in sites where palaeoecological reconstructions were performed (Valencia et al., 2016).

Each site has a characteristic landscape, that represents the dynamic of the site. Chorreras present marked patches of forest, dominated by Polylepis, Clethra, Gynoxys, and Miconia sp. Surucucho presents forest patches and extensions of grasslands showing human impact. Chochos presents big areas of montane forest, composed mainly of tropical alpine vegetation, some areas are still dammed by end-moraine. Pacucha is a zone heavily impacted by humans, montane forest is very low, due to deforestation. Refugio shows vegetation fragmented by grazing, there are scattered forest patches. Caserococha presents grasslands typical from the Andes and little forest areas. Huanmanmarca shows vast extensions of forests, areas register low-intensity grazing, and low human impact.

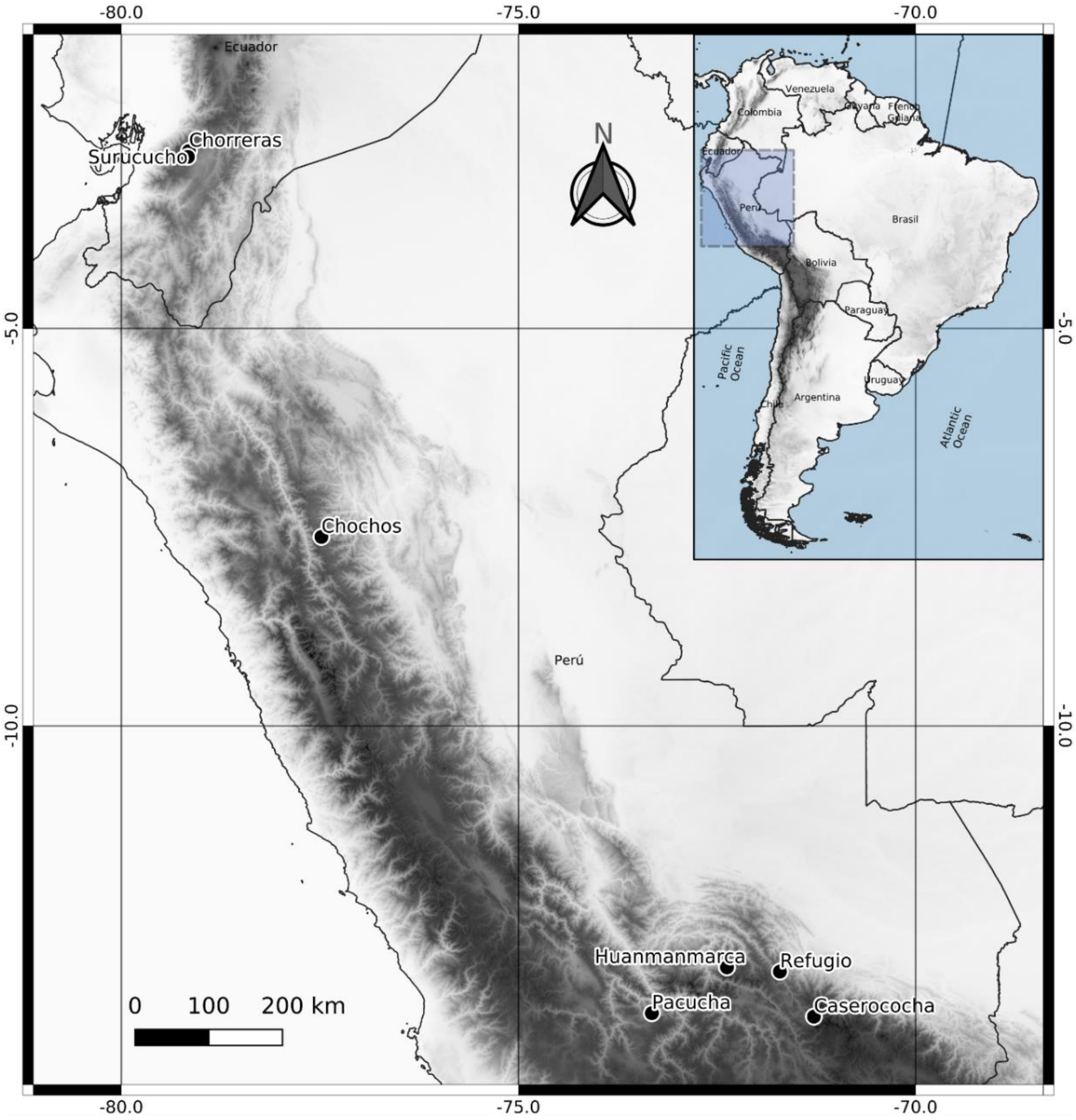

Figure 1. Spatial location of the seven sites

Methods

Each site is defined as a 25km buffer around the catchment where palaeoecological data was analyzed. We excluded two catchments (Miski and Khomer Kocha) from the original publication. The Miski catchment showed practically the same patterns of Huanmanmarca while Khomer Kocha lake doesn't present fire registers to be analyzed. To handle the vector data, we used the sf package (Pebesma, 2018), with tidyverse packages (Wickham et al., 2019). Landsat 8 images were downloaded from the United State Geological Survey (USGS) repository, using R statistical software and the getSpatialData package (R Core Team, 2020; Schwalb-Willmann & Fisser, 2020). The downloaded data contained seven Landsat 8 images filtered with a cloudiness less than 10 percent. Landsat images were used to calculate the Normalized Vegetation Index (NDVI). The NDVI was used to categorize the images into zones without vegetation, glaciers, rivers, and lakes, to be excluded from de analysis. We filtered NDVI values less or equal than 0.2, as it is considered as zones with lowest or non-vegetation (Long et al., 2019; Sobrino & Raissouni, 2000; Zaitunah, Samsuri, Ahmad, & Safitri, 2018).

Table 1. Physical characteristics of the study sites, two in Ecuador, five in Peru, number of fires per site in the 2015 year, and the date of landsat8 image.

Site	Latitude (S)	Longitude (O)	Mean altitude (m.a.s.l.)	Total analyzed area (km²)	Number of fires detected	Landsat8 image date
Caserococha	13°32'	71°39'	4472	2117.48	13	2015-06-26
Surucucho	2°84'	79°15'	3399	2323.22	1653	2016-11-20
Chorreras	2°77'	79°16'	3345	2225.67	1973	2016-11-20
Pacucha	13°60'	73°32'	3269	2672.33	23	2015-07-10
Refugio	13°09'	71°71'	3079	1944.06	3868	2017-07-24
Chochos	7°38'	77°28'	3099	2205.86	1481	2018-06-21
Huanmanmarc	13°03'	72°38'	3364	2050.61	4349	2018-07-27

The order of the sites is arranged by the median TRI value.

To test the influence of terrain roughness on fire occurrence we calculated the Terrain Roughness Index (TRI) for each site. TRI is based on the Riley method (Riley, DeGloria, & Elliot, 1999), which compares the elevation of a cell against the eight neighborhood cells using equation 1.

$$TRI = \left[\sum \left(x_{ij} - x_{00}\right)^2\right]^{1/2} \qquad \text{Equation 1}$$

Where: X_{ij} is the elevation of the neighbor pixel and X_{00} is the elevation of the central pixel. This process is implemented into the raster package (Hijmans, 2020). The TRI was computed using the function terrain. High TRI values represent steep irregular terrains and low TRI values represent plain terrains (Figure 2). The rugosity values were calculated from a digital elevation model (DEM) downloaded from the USGS repository. This DEM comes from the Shuttle Radar Topography Mission (SRTM) and has a resolution of 30m. The analyzed areas were screened to inspect topographic errors such as sudden depressions or peaks. The areas don't present inconsistences in their values.

The spatial distribution of fires was obtained from the Global Burned Area Map of 2015 (GABAM 2015). GABAM is a novel data set developed by Long et al., (Long et al., 2019) that provides a global burned product derived from Landsat 8 images at 30-meter resolution. We decided to use the GABAM data set because it allows the detection of smaller burned areas than other products as the Moderate Resolution Imaging Spectroradiometer (MODIS) Burned Area product (500m of resolution approximately). GABAM matches the TRI and NDVI spatial resolution of 30 m, so it avoids spatial resolution disparities.

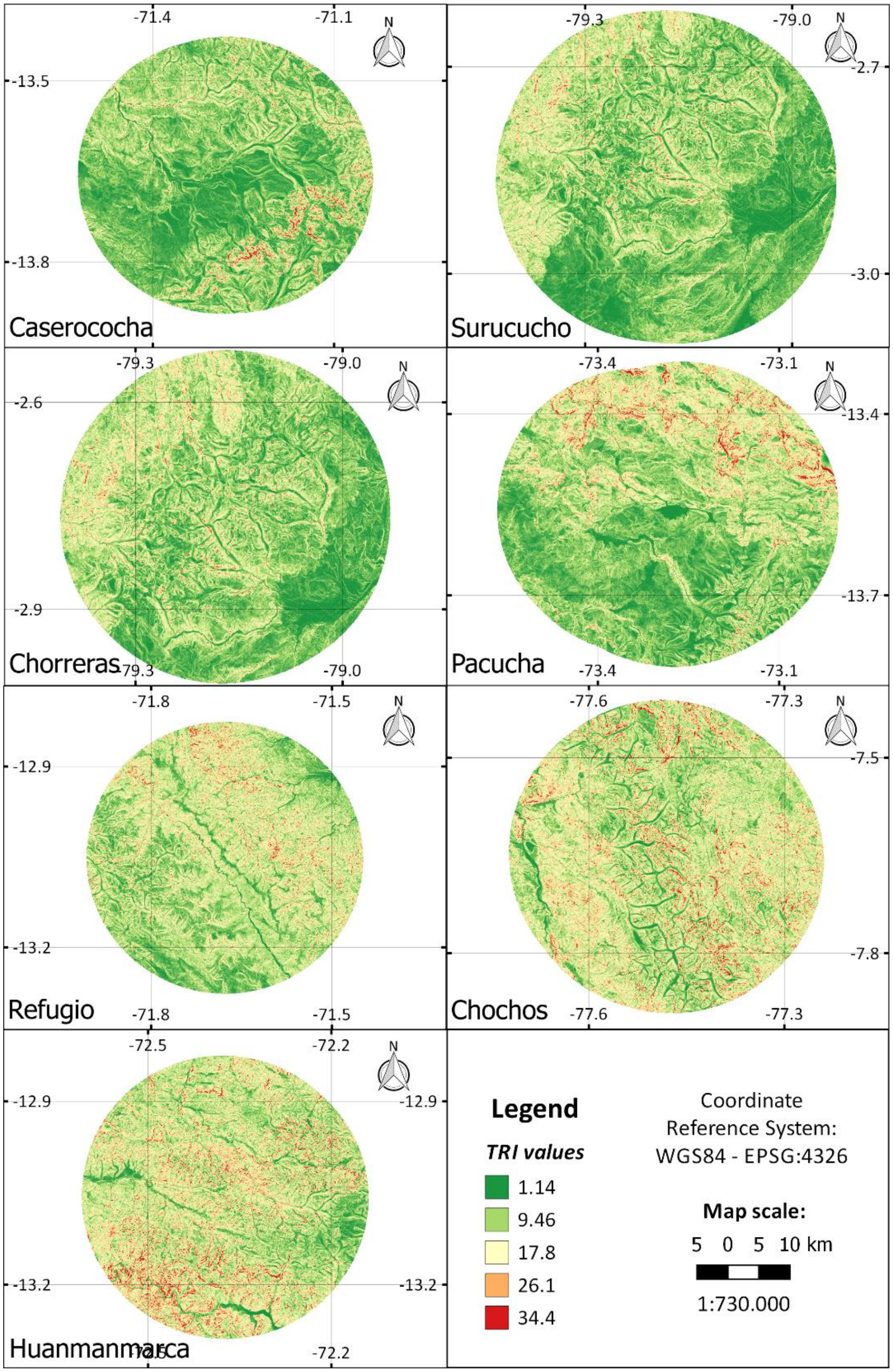

Figure 2. Representation of Terrain Rugosity Index for the seven sites. The order of the sites is arranged by the median TRI value. The color legend displays TRI values from low (green) to high values (red).

The data sets were re-projected to EPSG 4326 WGS84 and cropped according to the extent of each site. To analyze the data sets numerically, a crosstab process was computed between TRI, NDVI, and fires for each site. Crosstab process returned a table with values of TRI, NDVI, fires, and their frequency in each column. We divided the dataset into three parts, TRI values with fires (TRI_{fire}), TRI values with no fire presence ($TRI_{no\ fire}$), and the total TRI (TRI_{total}), which represent the sum of TRI_{fire} and $TRI_{no\ fire}$. To perform the statistical analysis, we took 500 random samples per each of three data sets and per each site. We repeated the random samples 100 times to avoid sampling biases in the data due to uneven number of observations. Then, we average the 100 random samples to make the graphical representation (Figure 4) and to perform the statistical analysis.

We compared the distribution of TRI values using probability density functions for TRI_{fire}, $TRI_{no\ fire}$, and TRI_{total} to observe if there were differences in their distribution. We used the Mann-Whitney Wilcoxon test, to evaluate if the TRI_{fire} zones were statistically different from the $TRI_{no\ fire}$ zones. Mann-Whitney Wilcoxon is a non-parametric test that evaluates if the data comes from similar populations, based on the median comparison. So, the hypothesis to test is that the TRI_{fire} zones and $TRI_{no\ fire}$ came from different populations. We used the coin package (Hothorn, Hornik, van de Wiel, & Zeileis, 2008) to perform the exact Mann-Whitney Wilcoxon test. The code used in this research can be found at https://gitlab.com/SGMStalin/fire_paper/-/tree/master/scripts

Results

The areas with the lowest fires detected were Caserococha and Pacucha compared to Refugio and Huanmanmarca that presented the largest number of fires. Chochos, Surucho, and Refugio showed an intermediate number of fires (Table 1). The main difference between the site with lowest fires and the site with the highest fires detected is in their TRI distribution. Caserococha is the site with the lowest minimum (6.07) and median (7.92) TRI values, while Huanmanmarca presented the highest median (15.4) and maximum (18.7) TRI values. The other sites had intermediate values and their TRI range are more extensive except Pacucha, which presented low number of fires.

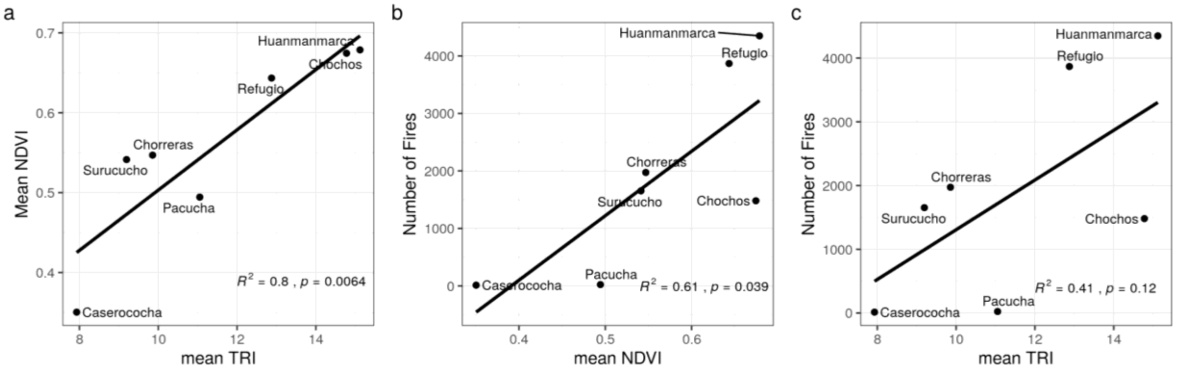

Figure 3. Correlation plots between Mean NDVI, mean TRI and number of fires. Panel (a) shows the correlation between mean TRI and mean NDVI. Panel (b) shows the correlation between mean NDVI and the number of fires. Panel (c) shows the correlation between mean TRI and the number of fires.

We found two positive significant correlations between the three variables analyzed. The highest correlation value was between the mean TRI and NDVI values (R^2=0.8, P=0.0064; Figure 3a), the second highest significant correlation was between NDVI and the number of fires (R^2 = 0.31, P = 0.039; Figure 3b). Finally, the lowest but non-significant correlation was between TRI and the number of fires (R^2 = 0.41, P = 0.119; Figure 3c).

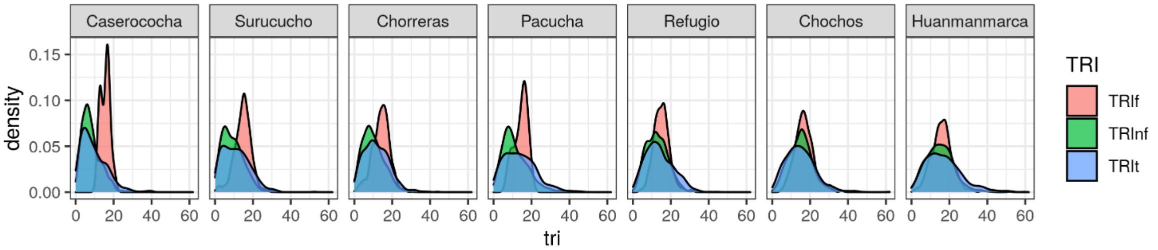

Figure 4. Density plots for the seven regions. The order of the regions is arranged by the median TRI value.

TRItotal values had smoothed peaks and the values were mostly concentrated between 0 to 30. TRIno fire values had more pronounced peaks (low variance), however, the TRIfire values had the largest and narrowest peaks (lowest variance), generally around 15, and the values had a lower range (10 to 20; Figure 4). The Mann-Whitney Wilcoxon test found statistical differences between TRIfire, TRIno fire, and TRItotal (p-value <= 2.2e-16; Table 2), which means that each variable comes from different populations. These results were consistent for all sites.

Table 2. Statistical differences between TRI_{fire} and $TRI_{no\ fire}$ using Mann-Whitney Wilcoxon for the seven sites.

Lake	Z	p-value
Caserococha	-6.16	2.2E-16
Surucucho	-27.37	2.2E-16
Chorreras	-27.37	2.2E-16
Pacucha	-8.11	2.2E-16
Refugio	-27.35	2.2E-16
Chochos	-26.77	2.2E-16
Huanmanmarca	-19.59	2.2E-16

The order of the regions is arranged by the median TRI value.

Discussion

It was hypothesized that sites with high terrain roughness (TRI) behave as barriers that prevented the spread of fires. Although this was observed at catchment level based on paleoclimate reconstructions, it was seldom tested in modern settings at regional scale (Valencia et al., 2016). If the proposed hypothesis was true, sites with high TRI are expected to have larger NDVI values (i.e., forest) than sites with low TRI. Our results (Figure 3a) showed a positive significant correlation between TRI and NDVI. Sites with heterogeneous terrains (high TRI) supported more forests (high NDVI) than those with flat terrains, which are characterized by reduced forest cover (low TRI, low NDVI). The significant positive correlation between NDVI and number of fire events (Figure 3b) suggest that fire events are commonplace in sites with high NDVI, and therefore high TRI. It may seem counterintuitive that sites experiencing the largest number of fires retain more forest area than sites with little fire where forests are small. One would expect little to no fire where forests persist, and frequent fire events where forests are absent. Fire events require three conditions to take place, (i) enough fuel (forest), (ii) dry conditions and (iii) an ignition source (Krawchuk, Moritz, Parisien, Van Dorn, & Hayhoe, 2009). High NDVI values (High TRI) represents fuel available on the landscape (forest) that can support fires. Sites with low NDVI indicate that biomass is insufficient or sparce to support fire. Small fires may still occur under low NDVI settings but may fall below the detection limit. Although specific dry conditions were not estimated, fire events were commonplace across the tropical Andes during the 2005 and 2010 droughts, suggesting all sites are equally affected by regional climate. As for the ignition source, humans are ubiquitous across the landscape and should induce more fires than lighting. The relevance of drought and ignition source were not disregarded as both are essential for fires to take place. However, the main goal of this study is to tackle fire dynamics taking a fuel-oriented perspective (high NDVI)

High NDVI occurs in areas with high TRI. It should be noted that high TRI does not prevent fire occurrence itself, but prevents fire spread. High TRI is analogous to landscape compartmentalization into discrete patches with terrain heterogeneity acting as perimeter fire-barriers. Consequently, fires should only affect small forest patches turning the landscape into a mosaic of forest and burned patches. Then, over several years, areas cleared by fire can be recolonized from neighboring forest patches unaffected by fire. Conversely, sites with low TRI are landscapes without fire barriers. When fire starts in forests with low TRI, fire can spread clearing large extensions of forests. In high Andean settings, recurrent fires promote the replacement of forests with grasslands or produces a transitional landscape where vegetation becomes sparse (Beerling & Osborne, 2006; Bush et al., 2015). Landscapes depleted in biomass (forest) may no longer support large fire events as biomass in low and discontinuous. Consequently, the non-significant correlation between TRI and the number of fires was expected (Figure 3c). The Caserococha and Pacucha sites have almost no fires. Palynological records retrieved at the center of these two sites have shown that local forests (*Polylepis* trees) were common prior to 13,000 years ago. However, recurrent fires eliminated the forests around 11,000 years ago in Pacucha and about 3000 years ago in Caserococha (Valencia et al., 2016). The low terrain heterogeneity (low TRI) should have favored fires that eliminated the forests at these two sites. The local forests did not recover once the forests were burned, probably because of short-lived grassland fires that prevented forest taxa colonization. It suggests that independently of the current human occupation, lower TRI sites are lesser favored to restore their vegetation than higher TRI sites. Consequently, low or discontinuous biomass should be factors limiting fires in the Pacucha and Caserococha sites as well as in mixed forests where fires should have a reduced impact (Alonzo et al., 2017).

The second hypothesis tests whether fires on the landscape are random. Each sites' TRI values were extracted for areas where fire occurred (TRI_{fire}), where fire was absent ($TRI_{no\ fire}$) and the entire site (TRI_{total}). We tested the null hypothesis of no significant differences between group distributions. If fire was a random process, then the three distributions, TRI_{fire}, $TRI_{no\ fire}$, and TRI_{total} were expected to overlap. A probability density function was used to depict the three distributions for each site studied (Figure 4). The Mann-Whitney Wilcoxon test indicated that highly significant differences existed between groups. It may seem that fires are more prone to occur in lower TRI values and near a TRI of 15, regardless of the sites or the type of vegetation. It's important to note that fires didn't occur in high TRI values even if there is vegetation. This, suggest that high TRI values also protect vegetation to be burned or make it less common. An explanation of this behavior could be that rugged terrains preserve cool temperatures and cloudiness (Blandford et al., 2008; Valencia et al., 2016), which prevents a possible ignition or propagation of fires. Overall, the peaks of the distributions for TRI_{fire} were consistently higher than $TRI_{no\ fire}$ in all the sites. However, sites like Caserococha and Pacucha, had a marked separation of the TRI_{fire} and

$TRI_{no\ fire}$ distribution peaks suggesting fires on these sites are less random than sites with near overlapping distributions. Conversely sites like Huamanmarca, Refugio and Chochos had significantly different distributions but higher overlap than the Pacucha or Caserococha sites (fire events tent to be more random than in Caserococha and Pacucha). If true, overlap differences could be used to infer the degree of anthropogenic landscape transformation in high Andean settings. Further testing is required, however.

The ongoing increase in wildfires and droughts has increased the interest in how climate change will influence fire activity (Rogers, Balch, Goetz, Lehmann, & Turetsky, 2020). However, the current knowledge of fires still has uncertainties, as the relationships between variables (i.e. climate, anthropogenic) remain unclear (Andela et al., 2017; Williams & Abatzoglou, 2016). Our findings allow us to (i) better understand fire regimes based on terrain heterogeneity and vegetation cover (NDVI) that are two accessible variables. Currently, the available studies focus on climatic variables excluding the influence of terrain rugosity in their analysis (Aldersley et al., 2011; Keeley & Syphard, 2016; Moritz et al., 2012). Including terrain roughness could improve results, especially to assess vulnerability to fire events when climate data is unavailable (ii) Landscape management can take place based on terrain heterogeneity. Our model suggests that sites with high TRI (> 12) and high NDVI (>0.5) have natural fire barriers allowing vegetation persistence acting as refugia. It's extremely important as future climate change projections estimate that warmer (droughts) seasons will affect the tropical Andes (Urrutia & Vuille, 2009). It means that more fires will occur especially in transition zones, as the recurrent droughts cause an increase in the fire frequency especially in the tropics (Krawchuk & Moritz, 2011). Thus, sites with lower TRI are vulnerable to fire events and have a lower probability to preserve their vegetation than sites with high TRI where fire barriers allow seedling development and regeneration of forests (Davis et al., 2019). In the climate change context, high TRI sites could work as refugia for both, vegetation, and animals. This behavior was identified in past scenarios. Even under extreme drought conditions and enhanced fire events, sites with high TRI retained more vegetation than sites with low TRI (Valencia et al., 2016). This information is extremely useful, regardless of the uncertainty of projected climate scenarios and allow the identification of areas that should be preserved. Especially those areas located between the western Amazonia and the Andes which are considered as areas with high priority to preserve the Amazonian biodiversity in the future climate change scenario (Hoorn et al., 2010; Miles, Grainger, & Phillips, 2004).

Finally, our study has some limitations. A problem with fires is the resolution of the data. We did a first approach with MODIS the fire product (it has a resolution of ~500m) and the fires identified were much lesser than the GABAM product. Having field information of fires in the analyzed areas could improve the analysis and results. We solve the scarce information of fires with GABAM product and buffers around sites used for paleoclimate reconstructions to test fire dynamics in modern landscapes. We suggest further research on fire dynamics and terrain roughness. Further researches can study this relationship with improved resolution data (i.e. field data) and including other variables (i.e. meteorological variables, land cover, land use, human influence).

Conclusions

Our results show that terrain roughness influence fire dynamics. Flat terrains, recurrent widespread fires that eliminate the vegetation (mainly forests) until the landscape cannot sustain large fires. Forest regeneration is slow over large areas and may be further constrained by grassland fires. Conversely, in rugged terrains, fires were unable to reduce the vegetation over large areas as fires affect discrete compartmentalized patches. Fires in rugged terrains generate a mosaic of forest and burned patches. Forest can regenerate in burned patches from neighboring forest. Currently, rugged zones present a higher frequency of fires due to the high available fuel. However, rugged terrains protect the vegetation since it prevents fire spread and facilitates the regeneration in burned patches.

Our analysis demonstrates that terrain roughness plays an important role in fire dynamics, especially at large temporal scales. Thus, rugged terrains could function as zones for the preservation of ecosystems and should be considered in conservation plans.

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