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The Paramo Fire Atlas: quantifying burned area and trends across the Tropical Andes

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Supplementary material for this article is available online

Abstract

The paramo ecosystem is vital for biodiversity conservation and water regulation. Despite fire being a known disturbance agent in this ecosystem, little is known about the frequency and trends in these high-elevation landscapes. To address this knowledge gap, we generated a novel burned area database, the Paramo Fire Atlas, spanning from 1985 to 2022 at 30 m resolution, quantifying the fire's impacts on the Paramo ecosystem across Colombia, Venezuela, Ecuador, and Peru. Using the complete Landsat archive, our database reveals that approximately 6370 km^2 has been affected by fires over 37 years, representing 15% of the total paramo area. Comparing these findings with estimates from the widely used MODIS MCD64 burned area product, we found that MODIS detected only 989 km^2 of burned area. This represents only one-fourth of the burned area detected by the Paramo Fire Atlas. This significant underestimation by MODIS underscores the limitations of existing data sources in assessing the fire impacts of this complex ecosystem. Contrary to the prevailing notion of increasing fire frequency, our analysis shows a significant decrease in burnt areas across the Colombia paramos, contrasting with heterogeneous trends observed in Ecuador and Peru and a recent peak in fire occurrence in Venezuela. While fires have largely disappeared from certain paramos, others exhibit varying degrees of change. These findings raise important questions about the role of fire disturbances in shaping the ecological functioning of the paramo and the future dynamics of fire in the paramo ecosystem under ongoing global climate change and socio-economical dynamics.

1. Introduction

The South American Paramo, a unique high-elevation ecosystem in the northern Andes, stands out for its remarkable biodiversity with over 4000 plant species and high levels of endemism (Bremer *et al* 2019, Hofstede and Llambí 2020). Moreover, they play an important role in carbon sequestration and providing water to most Andean urban settlements (Zomer and Ramsay 2021, Ledru *et al* 2022). Despite their social and ecological significance, paramos face several threats from both climate change and human activities (García *et al* 2020). As designated climate change hotspots, they are particularly vulnerable to temperature shifts, altered precipitation patterns, and extreme weather events (Correa *et al* 2020). Furthermore, a substantial portion of paramo areas has undergone conversion for agricultural and livestock production, contributing to habitat loss and increasing pressure on native flora and fauna while introducing invasive species and causing agricultural runoff that further degrades the ecosystem's integrity (Bremer *et al* 2019, Zomer and Ramsay 2021). This agricultural expansion employs fire as a main tool, making human-induced fires frequent across the paramo and a leading cause of extensive paramo degradation (Hofstede and Llambí 2020, Zomer and Ramsay 2021, Ledru *et al* 2022).

Although the role of fire in paramos is not yet fully understood, it is recognized as a significant disturbance agent that alters ecosystem structure and processes (Carrión-Paladines *et al* 2024). Fire can modify the structure and composition of the vegetation, influencing key ecological processes (Horn and Kappelle 2009, Gutiérrez-Salazar and Ramsay 2020). Even though the impact and effects of these fires depend on their frequency and intensity (Matson and Bart 2013), paramos recover at a slow rate after a fire event. This slow recovery is primarily due to their high-altitude location, characterized by extreme climatic conditions (Brück *et al* 2022, Mosquera *et al* 2023). These conditions lead to relatively low levels of primary productivity, slow growth, decomposition rates, and an overall slow natural succession rate (Hofstede *et al* 2002, Ledru *et al* 2022). Furthermore, burned areas may facilitate the establishment of non-native species, and high-frequency burning can diminish species diversity and increase soil exposure (Hofstede and Llambí 2020).

Much discussion exists about how adapted paramo ecosystems are to fire. One prevailing view suggests paramos are relatively pristine ecosystems with minimum natural disturbance, where climatic differences largely drive vegetation distribution (Carrillo-Rojas *et al* 2019). In contrast, an opposing viewpoint portrays paramo as a human-dominated landscape, where fire has been used throughout the Holocene, selecting against woody species (White 2013). The reality probably lies somewhere in between, as fires have been part of the paramo landscape before human occupation (Horn and Kappelle 2009). Yet, contemporary human activities such as agriculture and livestock production are now the region's main drivers of fire occurrence (Horn and Kappelle 2009, Bremer *et al* 2019, Grubb *et al* 2020, Zomer and Ramsay 2021). However, the comparison between prehistoric and present-day fire regimes and how current ecosystem functioning and structure are shaped by fire is still up for discussion (Sabogal 2023). While most fire ignitions nowadays are due to human activities, vegetation flammability depends on climate conditions, including rising temperatures, decreasing rainfall, and low vegetation humidity (Oliveras *et al* 2018). This aligns with expectations, as fire incidence in paramo regions is projected to grow due to the merged impacts of ongoing climate change and human interventions (Moreno *et al* 2019, Blake *et al* 2023). Moreover, local observations in some paramo sites corroborate this trend, with researchers reporting increased fire occurrences linked to livestock expansion and shifts in crop rotations (Hofstede and Llambí 2020, Zomer and Ramsay 2021). Nevertheless, as these existing studies only cover small portions of the paramo region, a critical knowledge gap remains regarding the specific characteristics of the paramo fire regime and its relationship with climate change in this ecosystem, impeding the formulation of informed ecological and conservation strategies (Zomer and Ramsay 2018).

One major obstacle in understanding fire's impact on paramos is the lack of reliable data on the annual extent of the burnt area across South American paramos and how this has changed through time. Global satellite products have been used to study fire occurrence in high-altitude Andean ecosystems (Bolaño-Díaz *et al* 2022, Zubieta *et al* 2023), but these products have many limitations and errors, often depending on the ecosystems' and landscapes' characteristics or the fire's size (Padilla *et al* 2015). Mapping fires in the paramo is challenging due to the cloudy conditions, complex topography, and the small size of the fires, raising concerns about the quality of the existing global burnt area products for these ecosystems.

The ongoing increasing availability of medium-resolution data through cloud computing platforms like Google Earth Engine enables the analysis of imagery using region-specific algorithms across large regions (Bastarrika *et al* 2024). Landsat imagery, with a spatial resolution of 30 meters and a temporal resolution of 16 d for Landsat 4, 5, 7, and 8, and 8 d for Landsat 9, enables long-term monitoring of fire activity dating back to the 1980s (Zhang *et al* 2022). In this study, we aim to quantify the burned area, frequency, and trends of fires across all South American paramos. Our primary objectives are to quantify the extent of burnt area across different paramos and to examine the hypothesis suggesting a recent increase in fire frequency over time. To achieve this, we created a database of the burned area of the South American paramos based on the Landsat archive spanning from 1985 to 2022.

2. Methods

2.1. Study area

The paramos of South America are distributed discontinuously along the Andes mountains of Colombia, Ecuador, Venezuela, and northern Peru (Peyre *et al* 2021), collectively covering approximately 35 000 km^2 (Zomer and Ramsay 2018). Situated between approximately 3000 and 5000 m above sea level, paramos cover the area above the Andean cloud forest up until the glaciers' snow line (Horn and Kappelle 2009, Hofstede and Llambí 2020). Vegetation within the paramos is characterized by herbaceous plants, rosettes, cushion plants, scrub, and patches of low-growing forest (Bremer *et al* 2019, Chuncho Morocho and Chuncho 2019).

2.2. Burned area mapping

We conducted the analysis using Landsat 4, 5, 7, 8, and 9 satellite imagery with a spatial resolution of 30 m, spanning the period from 1985 to 2022. The analysis employed the Landsat Level 2 Collection 2 Tier 1 product. For mapping burned areas, we utilized the Burned Area Cartography Tool developed by Roteta *et al* (2021), a tool developed to generate burned area maps for specific regions and time frames using a random forest classifier within the Google Earth Engine environment. The burnt area was mapped annually, but as the fire season frequently starts in December, the annual period goes from December to November of the following year to prevent splitting the fire season across two calendar years. More details about the burnt area mapping approach can be found in supplementary methods and figure S1. Using this approach, we created the Paramo Fire Atlas, an extensive database that provides raster-format burned area maps for the entire South American paramo region (burned area examples figures 1, S2 and S3).

2.3. Burned area product post-processing

We conducted two correction processes after obtaining the Paramo Fire Atlas initial product. First, we addressed the artificial gaps in burn scars caused by the malfunction of the Scan Line Corrector sensor (SLC-OFF) on the Landsat-7 ETM+ sensor, which has resulted in reduced scene coverage since 2003 (Wang *et al* 2021). This correction was carried out by manually filling evident gaps in burned scars throughout the South American paramos (example in figure S4) using ArcGIS 10.8. Second, we removed isolated burned pixels or patches containing up to three pixels unless at least one of them was within 30 meters of another burned pixel in any direction. This approach allowed us to retain pixels that, despite lacking immediate neighbors, were part of broader fire patterns while removing artifacts and individual pixel misclassifications that mainly represented image errors.

2.4. Accuracy assessment

2.4.1. Estimating omission errors using VIIRS thermal anomaly data

We investigate structural omissions in the dataset by examining the percentage of VIIRS S-NPP thermal anomalies (Schroeder *et al* 2014) not associated with any burn scar for each year over the 2013–2022 period. Leveraging their low commission error rates, thermal anomalies, defined by their distinct thermal spectral signature, are reliable fire activity indicators despite being prone to higher omission errors (Hantson *et al* 2013). For each paramo, we created buffers with a radius of 375 meters around each identified burned scar, matching the spatial resolution of the VIIRS S-NPP thermal anomalies at nadir. In the paramos located in the southwestern part of the study area (Ecuador and Peru), where the fire season typically starts in September and extends into November, we compared the burn scars from both the current and following year with the thermal anomalies of the current year. This approach ensures accuracy, as some burn scars are detected with a temporal lag of 1–2 months and may, therefore, be included in the subsequent fire year. Not including these fires would artificially increase our estimation of omission errors in these regions. To eliminate thermal anomalies associated with fires outside our study domain, we reduced the paramos boundaries with a 1 km buffer. We further manually removed thermal anomalies associated with active volcanoes within the study area. We then quantified the total number of VIIRS S-NPP thermal anomalies within the burned scar buffers for each paramo of the Paramo Fire Atlas. The percentage of thermal anomalies not associated with any burned scar was used to estimate the omission error for the paramo fire database.

2.4.2. Analyzing commission and omission errors using PlanetScope imagery

To assess the overall accuracy of the Paramo Fire Atlas, we computed commission and omission errors by comparing them to twenty reference burn scars, manually digitized using PlanetScope satellite imagery with a 3 m spatial resolution for 2021 and 2022 (Planet Team 2021). We randomly selected twenty fires across the study region by selecting twenty thermal anomalies from VIIRS S-NPP for 2021 and 2022. Subsequently, we downloaded cloudless Planet imagery taken before and after the dates of these thermal anomalies. Using the pre- and post-fire imagery, we manually digitized the burn scars. These manually digitized burn scars were then compared with the burned areas detected in the Paramo Fire Atlas (figure S5). Omission and commission errors were calculated, along with the relative bias for each individual fire, following the methodology of Padilla *et al* (2015). This approach uses error matrices to compare burned area data against high-resolution reference imagery. Relative bias was calculated as the difference between the burned area estimated by the Paramo Fire Atlas and the burned area mapped in the reference data, expressed as a proportion of the reference burned area.

2.4.3. Comparison of the Paramo Fire Atlas with the MODIS burnt area product

Most studies regarding fire occurrence in South America use existing global burnt area products, of which the MODIS burnt area product MCD64 (Giglio *et al* 2018) is by far the most widely used one (Bolaño-Díaz *et al* 2022, Oliveira *et al* 2022, Zubieta *et al* 2023). Here, we compare the burnt area detected by MCD64 with the burnt area detected by the Paramo Fire Atlas at an annual and country scale to detect whether the structural differences in burnt area magnitude and interannual variability are present between both datasets across the overlapping time period (2001–2022).

2.5. Annual burned area detection probability by country

The number of Landsat images available through time across the paramos is very variable, with years where few to no images are available to the present-day condition where multiple Landsat satellites are simultaneously acquiring imagery (figure S6). The changing availability of suitable imagery over time will impact the chance of detecting burned areas. To reliably track trends over time, we evaluated the annual probability of detecting burnt areas by analyzing the availability of cloud-free imagery. We initially grouped the paramos into twelve clusters based on proximity (figure 2) to capture geographic variations, adapting the classification made by Morales-Rivas *et al* (2007). Using VIIRS S-NPP thermal anomaly data, we identified the peak fire date for each paramo cluster as the last day of the fire season before thermal anomalies started to decline. For each year, we then calculated the absolute number of days between the peak fire date and the date of the first available cloud-free image for each pixel. Pixels with a minimum difference within a ±100 d window around the peak fire date were classified as detected. Conversely, pixels whose closest cloud-free image fell outside the ±100 d window were considered undetected, given that fire spectral signatures in the páramos generally dissipate beyond this period from the fire season.

For each of the twelve paramo groups, we conducted a linear regression analysis (figure S7) between the annual omission estimates based on VIIRS and three indicators of image availability: (i) the total number of detected pixels with spectral information, whether they correspond to burned or unburned areas, (ii) the number of pixels without spectral information due to clouds or other data gaps, and (iii) the number of pixels categorized as 100% detected. To increase data availability and broaden our predictor variables, we clustered pixel information from paramos with similar fire seasonality into Groups 1–5, Groups 6–8, and Groups 9–12. This approach allowed us to fit three regression models, which were used to estimate annual omission errors for each of the 12 paramo groups. The estimated annual omission for each paramo group was used to generate an estimated annual burnt area per country, considering the potential omission detected here.

3. Results

3.1. Burnt area occurrence across the paramos

Contrary to our initial expectations of extensive but isolated burning incidents, we found that a significant portion of the paramo vegetation has been affected by fire from 1985 to 2022 (figure 1). Our analysis detected burn scars across all South American paramo systems, with a total of 6370 km^2 burned during this period, equivalent to 15% of the total paramo area. To assess the extent of the burned area across different regions, we analyzed the South American paramos using the 12 spatial proximity groups (figure 2). Notably, the Perijá paramo, located along the Colombia-Venezuela border (Group 2), experienced the highest fire impact, with nearly 81% of its area burned. A parallel scenario unfolded in Sumapaz, located in central Colombia, part of Group 7 and the world's largest paramo, saw approximately one-third of its total area affected by fires, resulting in a fire-altered landscape mosaic (figure 1).

A distinct north-south gradient is evident, with burned areas increasing from Colombia and Venezuela towards the southern paramos of Ecuador and Peru. However, in Colombia, there is variation among regions. The paramos in the south of the Eastern Andes Cordillera (Group 7) and in the Sierra Nevada de Santa Marta (Group 1) show the highest levels of burned area. In contrast, the paramos in the Central (Group 6 and 8) and Western Cordilleras (Group 5) show much smaller burned areas. Further south, in Ecuador and Peru, this variability continues. The paramos in central Ecuador (Group 10) and in Peru (Group 12) exhibit extensive burned areas, while other regions in the northern area (Group 9) and southern Ecuador (Group 11) exhibit moderate levels of fire activity. These variations reflect the influence of both geographical and local conditions on fire regimes throughout the region.

3.2. Accuracy assessment

3.2.1. Omission errors using VIIRS thermal anomaly data by country

Between 2013 and 2022, Colombia and Ecuador registered the highest number of thermal anomalies, with 1489 and 1863 detections, respectively, with a lower number of thermal anomalies in Venezuela and Peru (tables 1 and S1). Overall, we observed low omission errors, with approximately 4.3% of the VIIRS thermal anomalies not associated with any burn scar from the Paramo Fire Atlas. However, important differences between the different countries can be observed. Ecuador had the highest omission rate among the studied countries, at 6.60%. Colombia and Peru have around 4% omission errors, while almost all thermal anomalies are associated with mapped burn scars across the Venezuelan paramos, with an omission error of 0.22%.

While these overall omission errors are relatively low, important differences between years can be observed (table S1). For Colombia, omission errors tend to fluctuate between 2%–5%, but some years that do show significant fire activity have 0% omission, while we find almost 15% omission for the year

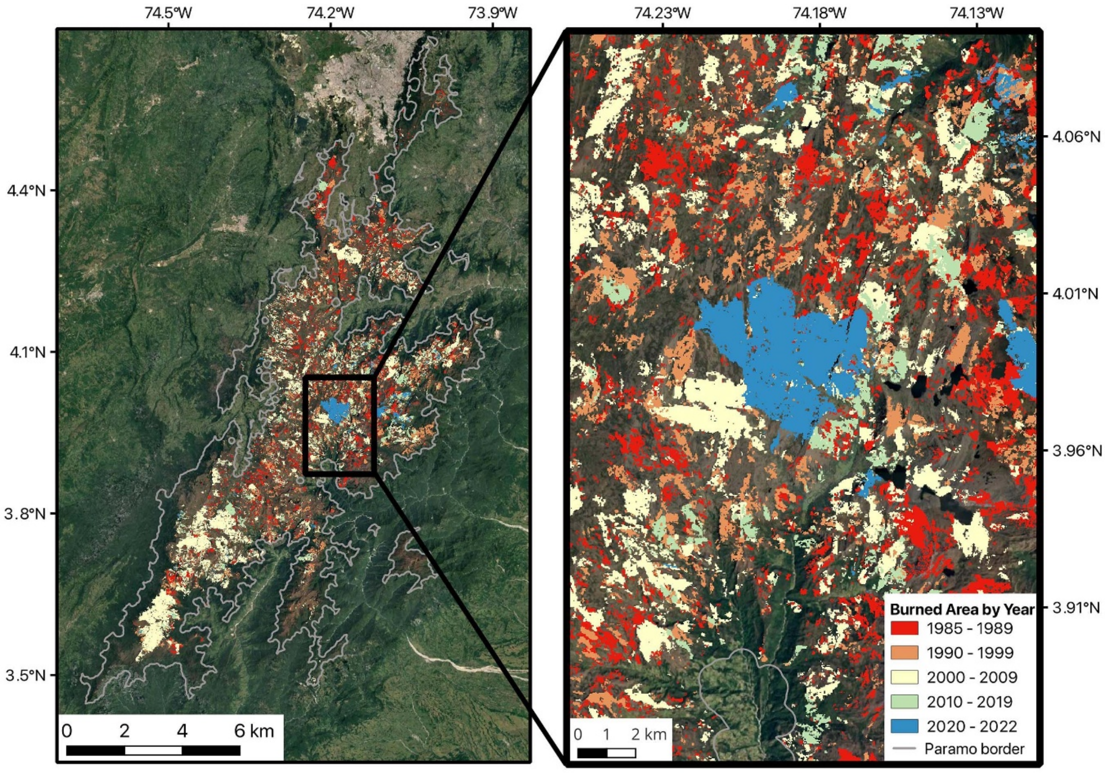

Figure 1. Example of burned area classification from the Paramo Fire Atlas in the Sumapaz paramo, Colombia, from 1985 to 2022. The image displays each pixel's last year of burn, illustrating fire events' spatial and temporal distribution. The right panel provides a zoomed-in view for more detailed visualization of burned areas.

2013. A similar pattern is observed in Ecuador, while the interannual variability in omission errors is more pronounced in Peru. In half of the years in Peru, all thermal anomalies correspond to burn scars identified by the Paramo Fire Atlas, whereas in the other years, omission errors of up to 25% are recorded. These results indicate the need to adequately consider these varying omission errors, especially when quantifying temporal trends, as the number of cloud-free images changes drastically throughout the study period (figure S6).

3.2.2. Commission and omission errors using PlanetScope imagery

A total of 20 randomly selected fires were used to quantify omission and commission errors based on high-resolution PlanetScope Imagery. Of these, 12 fires are located in Colombia, 2 in Venezuela, 4 in Ecuador, and 2 in Peru (table S2). Fire sizes varied, with the largest being 2.62 km^2 in Tota, Colombia, and the smallest at 0.03 km^2 in Peru. Overall, we find a low commission error (mean value of 7.7%), which indicates the high accuracy of the Paramo Fire Atlas when mapping burnt areas, with few false detections present. However, the mean omission error is higher, at 47.2%, although all fires except one were detected. Two examples of the comparison between the PlanetScope digitized burn scars and Paramo Fire Atlas can be observed in figure S5, where despite these relatively high omission errors, the areas missed are well-contained within the Planet-delineated boundaries. Altogether, we estimate a mean relative bias of −39.7%.

3.2.3. Comparison of burned area estimates between Paramo Fire Atlas and MODIS

A remarkable finding is the considerable disparity between the extent of burned areas detected by the Paramo Fire Atlas and those identified by the MODIS burned area product. The Paramo Fire Atlas revealed a substantially larger burned area, approximately four (4.3) times larger in extent, compared to the findings reported by the MODIS MCD64A1 Version 6.1 product (figure 3). MODIS product detected a mere 989.09 km^2 of burned area, equivalent to 2.3% of the total paramo area, while the Paramo Fire Atlas estimates 10% of all paramos being burned over the same period. The difference is especially noticeable during low fire years, where the MCD64 product often detects no burned pixels.

3.3. Trends in the annual burned area by country

Contrary to our initial hypothesis, no significant increase in burn area was observed for any country (figure 3). Instead, we found a significant decreasing trend in burnt areas for Colombia, the country which encompasses 61% of the total paramo extent. Large fire years in Colombia were primarily concentrated in the 1980s and early 1990 s, except for an exceptionally high peak in 2001 (figure 3(a)). This last

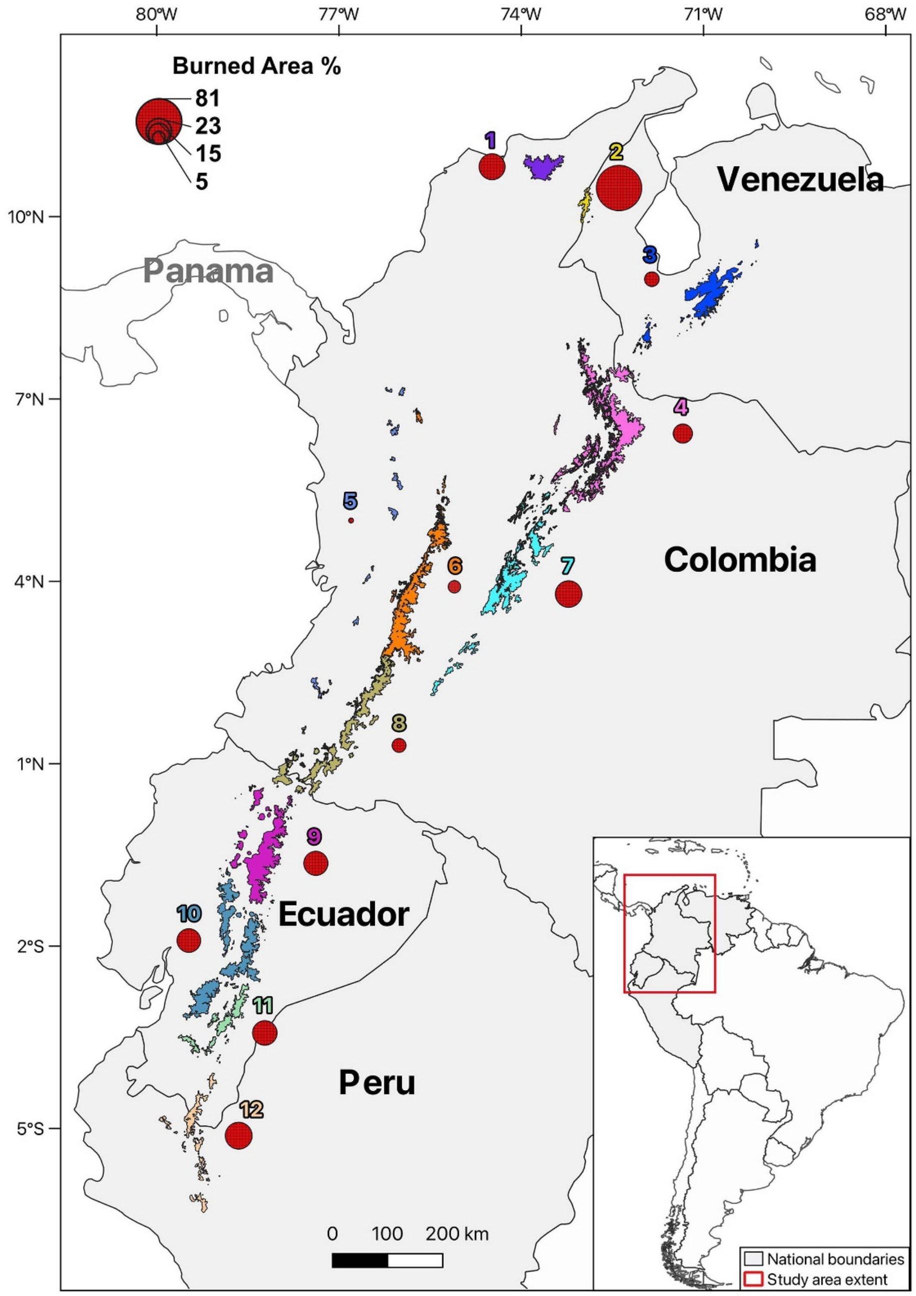

Figure 2. Percentage of burned area in paramo ecosystems across South America from 1985 to 2022. The data is divided into 12 groups based on geographic proximity, highlighting the varying impacts of fire across different paramo regions. Each group is color-coded and numbered, with the size of the red dots indicating the percentage of burned area for each group.

Table 1. Omission estimate based on VIIRS thermal anomalies. The number of thermal anomalies detected by VIIRS S-NPP in the paramo region of each country, along with the corresponding omission percentages from 2013 to 2022. Annual omission errors per country are provided in table S1.

Colombia		Venezuela		Ecuador		Perú	
Number of thermal anomalies	% Omission	Number of thermal anomalies	% Omission	Number of thermal anomalies	% Omission	Number of thermal anomalies	% Omission
1489	3.69	913	0.22	1863	6.60	414	4.35

peak in fire activity was consistent across other countries and correlated with findings from MODIS Terra thermal anomalies, reinforcing the robustness of our trend analysis (figure S8).

The trend analysis performed on the original data (red line in figure 3) might under or overestimate trends as we know that certain years have very low to zero image availability, compromising

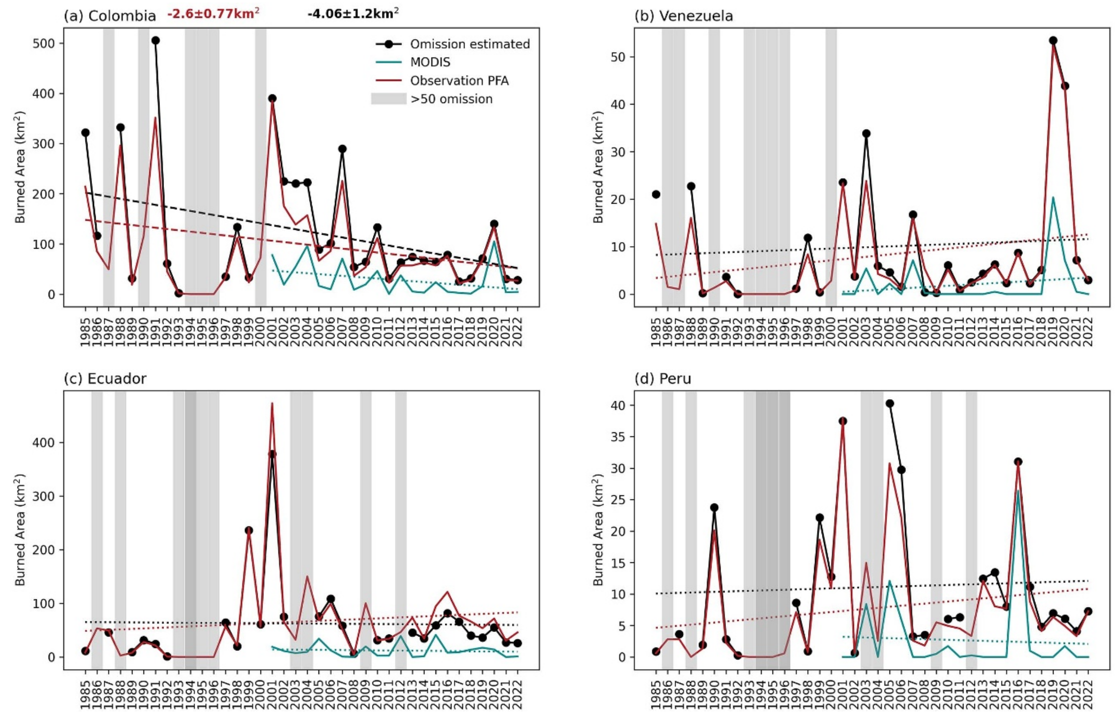

Figure 3. Annual burned area detected across the paramo region by country from 1985 to 2022. Continuous red lines indicate the initial burned area detected by the Paramo Fire Atlas. Continuous black lines represent the burned area estimates after applying the omission regression model. Blue lines represent the burned area detected by the MODIS MCD64A1 Version 6.1 product for comparison. Gray bars indicate years where the estimated omission rate is ⩾50%. Dashed lines represent the trend lines for the initially detected burned area (red) and the burned area after applying the omission model (black). Only Colombia shows significant trends, highlighted at the top of the panel (a).

the burnt area detection. This is especially evident, but not limited to, the 1980s and ‘90s. To account for this, we performed an estimate of these omission errors (see methods) and calculated an annual omission corrected burned area estimate (black line in figure 3). For years where omission errors exceeded 50%, we excluded those points from the trend analysis (black dotted line). Overall, the omission correction does not structurally change the observed patterns but strengthens the negative trends observed in Colombia and indicates that the (non-significant) positive trends in Peru and Venezuela are largely artifacts due to changing detection probabilities through time.

While burned areas were detected in most years across each country, there is a high inter-annual variability, with peaks concentrated in specific years (figure 3). One striking observation is the recent peak in burn areas in 2020–2021 across the Venezuelan paramos, a pattern that seems disconnected from any.

4. Discussion

The extensive database we compiled shows a consistent presence of fires in the South American paramos since the late 1980s. Despite year-to-year variations in fire occurrence, it is evident that the paramos do not represent an untouched and undisturbed ecosystem; rather, they are composed of a dynamic mosaic of successional stages shaped in part by frequent, small-scale fires. This lack of knowledge regarding paramos' fire dynamics is related to the historical underestimation that remote sensing products offered. The commonly used MODIS burned area product (Borelli *et al* 2015, Zapata-Ríos *et al* 2021) has limitations, as it only detects 23% of the burned area compared to our findings. Even considering the relatively high omission errors in the Paramo Fire Atlas, this striking divergence with MODIS emphasizes its contribution to providing a more extensive and accurate assessment of fire occurrences in these critical ecosystems.

Our findings align with the notion that paramos might be characterized as fire-dependent ecosystems, as previously suggested in studies (Horn and Kappelle 2009, Ramsay 2014). This concept implies that fire plays a crucial role in shaping the structure and composition of paramos (Zomer and Ramsay 2021). This is also in line with some functional traits of paramo vegetation towards fire, for example, paramo grasses that strategically protect their buds at the base or by rapidly regenerating leaves after a fire event (Gutiérrez-Salazar and Ramsay 2020). Additionally, experimental burns with low severity have shown minimal impact on paramo soil properties (Carrión-Paladines *et al* 2023). Despite these insights, the limited availability of data regarding paramo fire dynamics has led to fire suppression being considered the most effective strategy for conserving and managing the paramos (Zomer and Ramsay 2021). However, this approach may contribute to a reduction in species diversity within the paramos (Keating 2007).

Our initial hypothesis was that we would find an increase in burned area in recent years, as warming conditions and changing rainfall patterns have been indicated to cause fires to become more ubiquitous across the paramo (Oliveras *et al* 2018, Hofstede *et al* 2023). However, our results did not support this expectation, as we found no consistent upward trend in the burned area (figure 3). We find no trend in the burned area for most paramos and a negative trend for Colombian paramos. This result suggests that factors other than climate warming alone may regulate fire dynamics in this ecosystem, potentially related to localized land management practices (Díaz *et al* 2023).

Although our analysis did not reveal a consistent trend in fire activity across paramos, we observed substantial interannual variability, with several years of high fire occurrence and many with minimal burned area. This variability suggests a potential link between fire activity and extreme weather events in these ecosystems. While El Niño events are frequently associated with increased fire activity in South America (Oliveira-Júnior *et al* 2021) and have been linked to years of elevated fire incidence in the paramo (Borrelli *et al* 2015), our study did not find a consistent relationship between El Niño years and extensive burned areas. Notably, in 2001, a significant increase in burned area was observed across the four South American countries analyzed. This spike may be partially attributed to the La Niña event in the preceding year, as La Niña typically brings increased precipitation, promoting vegetation growth and fuel accumulation, which can elevate fire risk (Andela *et al* 2013, Corona-Núñez and Campo 2023).

Further, it is anticipated that the intensity and frequency of these extreme weather events and associated fire conditions will escalate due to climate change (UN 2022). Climate change is giving rise to a convergence of high temperatures, reduced humidity in vegetation, diminished rainfall, and intensified winds, significantly amplifying the likelihood of fire events (Smith *et al* 2020). Additionally, the influence of fires on carbon dynamics extends beyond paramo's immediate ecological boundaries. Paramos are known for their extensive underground carbon storage (Quiroz *et al* 2021), making them important components of the regional and global carbon cycles (Carrión-Paladines *et al* 2023). Thus, when fires impact these ecosystems, significant amounts of greenhouse gasses are released into the atmosphere, exacerbating the feedback loop with climate change (Veber *et al* 2018).

Our database provides a resource for exploring potential links between socioeconomic factors and fire dynamics in the South American paramos. For instance, peaks in burned areas in Venezuela during 2019 and 2020 closely followed the hyperinflation crisis in 2018 and subsequent economic collapse. This period may have driven some individuals who could not emigrate to seek livelihoods in previously unexploited regions (Rocha *et al* 2022). Although further research is needed to establish this connection, socioeconomic disruptions may transform paramos into emerging frontiers, reflecting similar patterns observed in Venezuela's savannas. While specific regional and national circumstances can exacerbate anthropogenic pressures on paramos, the persistent presence of fires in the paramos is a result of the expansion of human settlements in their proximity (Zapata *et al* 2021) and their important role providing essential food resources to Andean communities (Blake *et al* 2023).

While the Paramo Fire Atlas presents new data to analyze the occurrence and impact of fires within this key ecosystem, it is important to consider the limitations outlined in the results section when using the dataset. One key limitation is the underestimation of burnt areas during certain years due to limited imagery availability, particularly at the beginning of the time series when fewer Landsat images were available. Additionally, due to incomplete detection of burn scars (see figures S3 and S5), burnt area detection might still be underestimated, even when the burn scars are partially detected. This aspect might also complicate the usage of the dataset to analyze fire size and fire number by clustering burnt pixels.

Although fires have been an integral part of the dynamics across the paramo ecosystems, at least over the last decades, it is crucial to note that escalating anthropogenic changes in climate and land use could alter this process, posing challenges to paramos' resilience. We hope that the detailed mapping of and the long-time series of burned areas presented in the Paramo Fire Atlas will allow for assessing the impact of fires on paramos' biotic and abiotic components. An increase in understanding, in part, of present and future fire occurrence across the paramo is essential to inform policy and decision-makers, which can have far-reaching consequences for conservation efforts for the paramo ecosystem. These policies can include controlled burns, fire breaks, and managing fire-prone areas to simulate a natural process. Furthermore, recognizing the significant role of local communities in fire dynamics, this database can help identify target groups for involvement in policies that promote sustainable land use practices and reduce risks.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.12172679.

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References

Andela N, Liu Y Y, Van Dijk A I J M, De Jeu R A M and McVicar T R 2013 Global changes in dryland vegetation dynamics (1988–2008) assessed by satellite remote sensing: comparing a new passive microwave vegetation density record with reflective greenness data *Biogeosciences* **10** 6657–76

Bastarrika A *et al* 2024 An automatic procedure for mapping burned areas globally using Sentinel-2 and VIIRS/MODIS active fires in Google Earth Engine *ISPRS J. Photogramm. Remote Sens.* **218** 232–45

Blake L J, Chohan J K and Escobar M P 2023 Agro-extractivism and neoliberal conservation: campesino abandonment in the Boyacá páramos, Colombia *J. Rural Stud.* **102** 103071

Bolaño-Díaz S, Camargo-Caicedo Y, Soro T D, N'Dri A B and Bolaño-Ortiz T R 2022 Spatio-temporal characterization of fire using MODIS data (2000–2020) in Colombia *Fire* **5** 134

Borrelli P, Armenteras D, Panagos P, Modugno S and Schütt B 2015 The implications of fire management in the Andean Paramo: a preliminary assessment using satellite remote sensing *Remote Sens.* **7** 11061–82

Bremer L L, Farley K A, Demaagd N, Suárez E, Cárate Tandalla D, Vasco Tapia S and Mena Vásconez P 2019 Biodiversity outcomes of payment for ecosystem services: lessons from páramo grasslands *Biodivers. Conserv.* **28** 885–908

Brück S A, Contato A G, Gamboa-Trujillo P, De Oliveira T B, Cereia M and De Moraes Polizeli M D L T 2022 Prospection of psychrotrophic filamentous fungi isolated from the high Andean Paramo region of Northern Ecuador: enzymatic activity and molecular identification *Microorganisms* **10** 282

Carrillo-Rojas G, Silva B, Rollenbeck R, Célleri R and Bendix J 2019 The breathing of the Andean highlands: net ecosystem exchange and evapotranspiration over the páramo of southern Ecuador *Agric. For. Meteorol.* **265** 30–47

Carrión-Paladines V, Correa-Quezada L, Valdiviezo Malo H, Zurita Ruáles J, Pereddo Tumbaco A, Zambrano Pisco M, Lucio Panchi N, Jiménez Álvarez L, Benítez Á and Loján-Córdova J 2024 Exploring the ethnobiological practices of fire in three natural regions of Ecuador, through the integration of traditional knowledge and scientific approaches *J. Ethnobiol. Ethnomed.* **20** 60

Carrión-Paladines V, Fries A, Hinojosa M B, Oña A, Álvarez L J, Benítez Á, Rodríguez F L and García-Ruiz R 2023 Effects of low-severity fire on soil physico-chemical properties in an Andean Páramo in Southern Ecuador *Fire* **6** 447

Chuncho Morocho C and Chuncho G 2019 Páramos del Ecuador, importancia y afectaciones: una revisión *Bosques Latit. Cero* **9** 71–83 (available at: https://revistas.unl.edu.ec/index.php/bosques/article/view/686)

Corona-Núñez R O and Campo J E 2023 Climate and socioeconomic drivers of biomass burning and carbon emissions from fires in tropical dry forests: a Pantropical analysis *Glob. Change Biol.* **29** 1062–79

Correa A, Ochoa-Tocachi B F, Birkel C, Ochoa-Sánchez A, Zogheib C, Tovar C and Buytaert W 2020 A concerted research effort to advance the hydrological understanding of tropical páramos *Hydrol. Process.* **34** 4609–27

Díaz S C, Quezada L C, Álvarez L J, Loján-Córdova J and Carrión-Paladines V 2023 Indigenous use of fire in the paramo ecosystem of southern Ecuador: a case study using remote sensing methods and ancestral knowledge of the Kichwa Saraguro people *Fire Ecol.* **19** 5

García V J, Márquez C O, Rodríguez M V, Orozco J J, Aguilar C D and Ríos A C 2020 Páramo ecosystems in ecuador's Southern Region: conservation State and Restoration *Agronomy* **10** 1922

Giglio L, Boschetti L, Roy D P, Humber M L and Justice C O 2018 The Collection 6 MODIS burned area mapping algorithm and product *Remote Sens. Environ.* **217** 72–85

Grubb P J, Lloyd J R, Pennington T D and Páez-Bimos S 2020 A historical baseline study of the páramo of Antisana in the Ecuadorian Andes including the impacts of burning, grazing and trampling *Plant Ecol. Diversity* **13** 225–56

Gutiérrez-Salazar P and Ramsay P M 2020 Physiognomic responses of páramo tussock grass to time since fire in northern Ecuador *Rev. Peruana Biol.* **27** 205–14

Hantson S, Padilla M, Corti D and Chuvieco E 2013 Strengths and weaknesses of MODIS hotspots to characterize global fire occurrence *Remote Sens. Environ.* **131** 152–9

Hofstede R G M and Llambí L D 2020 *Plant Diversity in Páramo—Neotropical High Mountain Humid Grasslands* (Elsevier) pp 362–72

Hofstede R, Coppus R, Mena-Vásconez P, Segarra P, Wolf J and Sevink J 2002 The conservation status of tussock grass paramo in Ecuador *Ecotropicos* **15** 3–18

Hofstede R, Mena-Vásconez P and Suárez Robalino E 2023 El cambio climático en el páramo del Ecuador *Los Páramos Del Ecuador: Pasado, Presente Y Futuro* ed R Hofstede, P Mena-Vásconez and E S Robalino (USFQ Press) pp 324–52

Horn S P and Kappelle M 2009 *Fire in the Páramo Ecosystems of Central and South America* (Springer Berlin Heidelberg) pp 505–39

Keating P L 2007 Fire ecology and conservation in the high tropical Andes: observations from Northern Ecuador *J. Latin Am. Geogr.* **6** 43–62 (available at: www.jstor.org/stable/25765157)

Ledru M-P, Aquino-Alfonso O, Finsinger W, Samaniego P and Hidalgo S 2022 Changes in the vegetation and water cycle of the Ecuadorian páramo during the last 5000 years *Holocene* **32** 095968362211012

Matson E and Bart D 2013 Interactions among fire legacies, grazing and topography predict shrub encroachment in post-agricultural páramo *Landscape Ecol.* **28** 1829–40

Morales-Rivas M *et al* 2007 *Atlas de páramos de Colombia* (Instituto de Investigación de Recursos Biológicos Alexander von Humboldt)

Moreno L A, Andrade G I and Gómez M F 2019 Biodiversidad 2018. Estado y tendencias de la biodiversidad continental de Colombia (Instituto de Investigación de Recursos Biológicos Alexander von Humboldt) (available at: http://reporte.humboldt.org.co/biodiversidad/)

Mosquera G M *et al* 2023 Frontiers in páramo water resources research: a multidisciplinary assessment *Sci. Total Environ.* **892** 164373

Oliveira U, Soares-Filho B, Bustamante M, Gomes L, Ometto J P and Rajão R 2022 Determinants of fire impact in the Brazilian biomes *Front. For. Glob. Change* **5** 735017

Oliveira-Júnior J F D *et al* 2021 Fire foci in South America: impact and causes, fire hazard and future scenarios *J. South Am. Earth Sci.* **112** 103623

Oliveras I *et al* 2018 Fire effects and ecological recovery pathways of tropical montane cloud forests along a time chronosequence *Glob. Change Biol.* **24** 758–72

Padilla M *et al* 2015 Comparing the accuracies of remote sensing global burned area products using stratified random sampling and estimation *Remote Sens. Environ.* **160** 114–21

Peyre G, Osorio D, François R and Anthelme F 2021 Mapping the páramo land-cover in the Northern Andes *Int. J. Remote Sens.* **42** 7777–97

Planet Team 2021 Planet application program interface: in space for life on earth (available at: https://api.planet.com)

Quiroz Dahik C, Crespo P, Stimm B, Mosandl R, Cueva J, Hildebrandt P and Weber M 2021 Impacts of pine plantations on carbon stocks of páramo sites in southern Ecuador *Carbon Balance Manage.* **16** 1–15

Ramsay P M 2014 Giant rosette plant morphology as an indicator of recent fire history in Andean páramo grasslands *Ecol. Indic.* **45** 37–44

Rocha A, Gomes Da Silva C and Perobelli F 2022 The new economic geography and labour emigration: analysing Venezuela's hyperinflation episode *J. Int. Dev.* **34** 175–202

Roteta E, Bastarrika A, Franquesa M and Chuvieco E 2021 Landsat and Sentinel-2 based burned area mapping tools in google earth engine *Remote Sens.* **13** 816

Sabogal A 2023 The Paramo Ecosystems *Ecosystem and Species Adaptations in the Andean-Amazonian Region* (Springer International Publishing) pp 105–30

Schroeder W, Oliva P, Giglio L and Csiszar I A 2014 The New VIIRS 375 m active fire detection data product: algorithm description and initial assessment *Remote Sens. Environ.* **143** 85–96

Smith A J P, Jones M W, Abatzoglou J T, Canadell J G and Betts R A 2020 Climate change increases the risk of wildfires (Zenodo) (https://doi.org/10.5281/zenodo.4570195)

United Nations Environment Programme 2022 *Spreading like Wildfire—The Rising Threat of Extraordinary Landscape Fires* (A UNEP Rapid Response Assessment)

Veber G, Kull A, Villa J A, Maddison M, Paal J, Oja T, Iturraspe R, Pärn J, Teemusk A and Mander Ü 2018 Greenhouse gas emissions in natural and managed peatlands of America: case studies along a latitudinal gradient *Ecol. Eng.* **114** 34–45

Wang Q, Wang L, Wei C, Jin Y, Li Z, Tong X and Atkinson P M 2021 Filling gaps in Landsat ETM+ SLC-off images with Sentinel-2 MSI images *Int. J. Appl. Earth Observ. Geoinf.* **101** 102365

White S 2013 Grass páramo as hunter-gatherer landscape *Holocene* **23** 898–915

Zapata-Ríos X, Lopez-Fabara C, Navarrete A, Torres-Paguay S and Flores M 2021 Spatiotemporal patterns of burned areas, fire drivers, and fire probability across the equatorial Andes *J. Mount. Sci.* **18** 952–72

Zhang Y, Woodcock C E, Chen S, Wang J A, Sulla-Menashe D, Zuo Z, Olofsson P, Wang Y and Friedl M A 2022 Mapping causal agents of disturbance in boreal and arctic ecosystems of North America using time series of Landsat data *Remote Sens. Environ.* **272** 112935

Zomer M A and Ramsay P M 2018 Espeletia giant rosette plants are reliable biological indicators of time since fire in Andean grasslands *Plant Ecol.* **219** 79–88

Zomer M A and Ramsay P M 2021 Post-fire changes in plant growth form composition and diversity in Andean páramo grassland *Appl. Vegetation Sci.* **24** e12554

Zubieta R, Ccanchi Y and Liza R 2023 Performance of heat spots obtained from satellite datasets to represent burned areas in Andean ecosystems of Cusco, Peru *Remote Sens. Appl.* **32** 101020