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Spatiotemporal Fire Patterns and Post-fire Forest Change in Peru (2000–2021)

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ABSTRACT

Fire is increasingly more frequent and severe in many tropical regions, leading to significant forest loss, diminished biodiversity, and reduced Nature's contributions to people (NCPs). In this study, we analyzed the spatiotemporal patterns of fire in Peru and its regions, focusing on: (1) burned area, (2) size, and (3) number of fires, using satellite data spanning two decades (2001–2020). Furthermore, we examined postfire changes in forest and shrubland. Our analysis revealed that 2.1 million hectares were burned in Peru, with over 80% of this area located in the Andean and Low Rainforest regions. Distinct fire seasonality was observed. The years 2005, 2010, 2016, 2019, and 2020 witnessed extensive burns across Peru, while the Coast region experienced peak fires in 2016 and 2017. Notably, the Coast region saw an increasing trend in fire frequency, and both the Coast and Andean regions experienced growth in fire size over time. Factors such as the dry season, El Niño-Southern Oscillation (ENSO), and land-use activities were found to influence these spatiotemporal patterns. Grasslands were the most burned land cover, followed by savannas and forests, although regional variations exist. Significantly, we found that nearly half or more of burned forests and shrublands underwent a transformation to different land covers within the two decades. While grasslands were the dominant postfire land cover nationally, regional variations were evident. Our findings offer a comprehensive insight into the fire dynamics and postfire cover shifts in Peru, underscoring the need for developing strong and sustainable fire management and land-use policies.

1 | Introduction

Fire is a natural phenomenon that plays a key role in the dynamics of many terrestrial ecosystems (Bowman et al. 2009). However, it is also an anthropogenic disturbance closely linked to land use and land cover changes—particularly for agricultural clearing and/or livestock grazing (Cochrane 2003). Therefore, fire activity is a complex interaction of bioclimatic conditions and human factors (Jones et al. 2022). Its impact on biodiversity and human well-being is significant, particularly, through the disruption of Nature's contributions to people (NCPs) such as carbon and climate regulation, water regulation, and soil formation (He et al. 2019; Giorgis et al. 2021; Krisnawati et al. 2021). NCPs expand the concept of ecosystem services by recognizing

the co-production of benefits through interactions between nature and people, shaped by both traditional practices and scientific knowledge (Díaz et al. 2015).

While global burned area has declined on average (Andela et al. 2017), fire frequency and intensity have increased in many fire-prone regions, as well as in areas not historically affected by fire (Armenteras 2022; García et al. 2022; Souza-Alonso et al. 2022; Wu et al. 2023). This trend is largely driven by climate change, land use transformations, and evolving fire policies. In tropical ecosystems, fire has become more recurrent in recent years, leading to long-term alterations in biomass and ecosystem structure (Armenteras 2022; García et al. 2022; Souza-Alonso et al. 2022). These transformations are often

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associated with deforestation and degradation processes such as repeated burning, forest fragmentation, and overgrazing, which undermine ecosystem resilience and increase vulnerability (De Sy et al. 2019; Armenteras 2022; Lapola et al. 2023). Other underlying factors—such as armed conflict, weak governance, or invasive species—may also influence fire regimes (Armenteras et al. 2020; Souza-Alonso et al. 2022), though they are less measurable in spatial scope.

South American landscapes include a variety of biomes and ecosystems increasingly affected by fires (Giorgis et al. 2021; Armenteras 2022; Souza-Alonso et al. 2022). Fire regimes vary depending on the ecological characteristics, vegetation types, and climatic gradients. These systems can be categorized into three types (Armenteras 2022): fire-dependent (grasslands, savannas, and the Cerrado; Silva et al. 2021), fire-sensitive (dry forests and high-altitude ecosystems: punas and paramos), and fire-independent (rainforests, shrublands, and wetland ecosystems such as the Pantanal; Correa et al. 2022). Moreover, the differences in species composition and structure, intrinsic fuel properties of vegetation (moisture, ignitability, and the heat released during combustion), and decay all interact to dictate the ability of a fuel to burn, that is, flammability (Souza-Alonso et al. 2022).

In tropical forests, fire occurrences are often associated with deforestation processes—that is, clearing the ground using fire for agricultural activities—and climatic events (Armenteras et al. 2021). Global warming contributes to increasing the frequency and intensity of fires through anomalies in ocean-surface temperature and alterations in “El Niño” Southern Oscillation (ENSO), which can simultaneously cause extreme droughts and heavy rainfall or flooding in different parts of the region affecting tropical ecosystems (Chen et al. 2011). In the lowlands of Amazonia, fire has become more recurrent and intense in recent decades, particularly, during extreme “El Niño” droughts (Silva Junior et al. 2019; Pontes-Lopes et al. 2021). Similar trends have been observed in the Andes (Román-Cuesta et al. 2011), where fire activity has intensified in association with extended dry seasons, drought events, and climatic variability during “El Niño”–“La Niña” transitions (Román-Cuesta et al. 2014; Zubieta 2019; Zubieta et al. 2021). Tropical montane forests have also been affected by recurrent fires (Román-Cuesta et al. 2011; Oliveras et al. 2014; Zubieta et al. 2021). While fires are part of the natural regime in dry forests, their current frequency has increased, driven by more intense and prolonged drought periods linked to “El Niño” variability (Schröder et al. 2021).

While our understanding of the impact of fire in South American biomes and ecosystems has increased in recent decades, critical information gaps persist, especially in dry forests, punas, and montane and lowlands rainforests. Additionally, the limited or lack of reliable national fire statistics, fragmented institutional coordination, and unviable ban policies in the region inhibit useful fire management policies (Armenteras et al. 2020; Armenteras and de la Barrera 2023). This is, particularly, alarming in a changing context where fires are expected to be intensified (De Faria et al. 2017; Armenteras et al. 2021). Consequently, long-term analyses of fire frequency, seasonality, and spatial dynamics are needed to guide sustainable land use decisions (Armenteras 2022).

Fires account for a substantial share of global forest loss, nearly a quarter of the global total between 1990 and 2015 (Curtis et al. 2018). Moreover, about 0.36%–0.74% of the global burned areas experienced a postfire change in the land use of the land cover, mostly from forest to agriculture (Wu et al. 2023). In South America, postfire transitions frequently involve conversion to savannas and grasslands, with cross-country differences in rates and timing (Armenteras et al. 2021).

Postfire natural regeneration depends on multiple interacting factors, including fire history, burn severity (i.e., the degree of soil organic matter loss), availability of viable seed banks, herbivory, invasive species, soil compaction, microclimatic conditions, continued grazing, lack of protection, and other human pressures (Hardesty et al. 2005; Shlisky et al. 2007; Souza-Alonso et al. 2022). Different fire regimes can cause the succession process to follow different recovery trajectories (Zhou et al. 2019). Although ecological succession can transform deforested areas into secondary forests after fire, land cover and land use changes might result from other causes, such as forest cutting, grazing, agriculture, or other human activities (Souza-Alonso et al. 2022; Wu et al. 2023).

Even though some tropical forests show resilience to initial disturbances, increments in severity and frequency of fire have significantly altered forest structure (Butchart et al. 2012; Armenteras et al. 2017; Lapola et al. 2023). As a result, these disturbed forests are more vulnerable to fire and other disturbances and reduce their NCPs and biodiversity values in comparison with nondisturbed or primary forests (Hirota et al. 2011; Uriarte et al. 2016; Giorgis et al. 2021). Our understanding of postfire land cover change in tropical South America biomes and ecosystems remains unclear while tropical deforestation and degradation continue. Therefore, examining trajectories of land cover change postfire at different scales is still necessary (Zhou et al. 2019; Armenteras et al. 2021; Souza-Alonso et al. 2022; Wu et al. 2023).

Peru boasts a rich topographical, ecological, and climatological diversity, with forests constituting approximately 60% of its landscape (MINAM (Ministerio del Ambiente Perú) 2019; FAO (Food and Agriculture Organization Organization of the United Nations) 2020). The nation has witnessed a rising trend in fires, particularly in its diverse ecosystems, ranging from dry forests, punas, to montane and lowlands rainforests (SENAMHI-MINAM (Servicio Nacional de Meteorología e Hidrología del Perú—Ministerio del Ambiente del Perú) 2018). Despite there being scarce information, an estimated 90% of these fires are attributed to human activities, predominantly linked to pastures and agriculture (SERFOR-MIDAGRI (Servicio Nacional Forestal y de Fauna Silvestre—Ministerio de Agricultura y Riego) 2018; MINAM (Ministerio del Ambiente del Perú) 2023). While fire monitoring has improved in recent years, national datasets have largely relied on case reports and transitioned to satellite-based data (SENAMHI-MINAM (Servicio Nacional de Meteorología e Hidrología del Perú—Ministerio del Ambiente del Perú) 2018; Figure A6). This situation, together with challenges related to institutional coordination, long-term monitoring, and gaps in technical and policy integration, has contributed to the still limited number of fire regime studies in Peru,

particularly in forested areas. Most contemporary literature either emphasizes climatic or vegetation conditions for fires (Zubieta 2019; Zubieta et al. 2021) or focuses on fire risk indices (Podschwit, Jolly, Alvarado, Verma, et al. 2022; Podschwit, Jolly, Alvarado, Markos, et al. 2022). Global research efforts have primarily targeted the Andean (Oliveras et al. 2014, 2018; Zubieta et al. 2021) and the Amazonian ecosystems, with the latter being explored both as part of international collaborations (Cardil et al. 2020; Armenteras et al. 2021; Singh and Zhu 2021; Ferreira et al. 2023) or specific regional studies (Román-Cuesta et al. 2011; Oliveras et al. 2014; Vincent 2018).

In this study, we analyze the spatiotemporal dynamics of fires, the land covers affected, and the postfire transformation of forests and shrublands across Peru from 2001 to 2020. We address three questions: (1) How do fire occurrences in Peru vary spatiotemporally and across regions? (2) Which land covers are affected by these fires? (3) How do burned forests and shrublands change postfire? By integrating spatial fire patterns and land cover dynamics, this study offers valuable insights to inform land-use planning, fire governance, and conservation policy. It also provides novel, country-wide evidence on fire regimes in Peru—an area of research still evolving—and serves as a reference point for future research and the strengthening of national fire management strategies. In particular, the findings lay the groundwork for future assessments of how fires may be affecting key NCPs, such as carbon regulation, water availability, and landscape resilience.

2 | Materials and Methods

2.1 | Study Area

The study area corresponds to entire Peru, the third largest country of the continent, located in central-western South America (1.28 million km²; IGN (Instituto Nacional Geográfico) 2021). To capture regional variations in fire, we defined four regions (Figure 1a) that are topographically, climatically, and ecologically distinct according to (MINAM (Ministerio del Ambiente Perú) 2019):

1. The Coast region (10% of the country area) is a narrow portion dominated by extensive plains and the first Andean hills (height around 1500–2000 m). It is mainly hot and dry. The dry forests in the northwest, shrublands, wetlands, and the arid desert are the main ecosystems of the region.
2. The Andean region (30%) has a sloped to extremely steep relief corresponding to the Andes mountains that dissect the country from North to South, with its highest point at more than 6700 m. The climate ranges from semiwarm arid to cold wet or cold dry, with a dry season. Its prevailing are grasslands, shrublands, paramos, wetlands, and relict forests.
3. The High Rainforest region (14%) is on the eastern Andean slope, with a humid or subhumid climate, permanent fog, and steep slopes. Here, montane forests are predominant, varying in structure according to the proximity to the Andes.

4. The Low Rainforest region (46%) is in the eastern part of the country. It is a humid and rainy area with seasonal or permanently flooded forest and other hydromorphic ecosystems.

2.2 | Data Sources

We used the MCD64A1 Version 6.1 Burned Area product from 2001 to 2020, a monthly dataset at 500 m resolution derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's TERRA satellite (Giglio et al. 2021). We selected this dataset for its consistency, long-term coverage, and suitability for large-scale fire occurrence analyses. This product was selected due to its consistency, long-term coverage, and suitability for large-scale fire occurrence analyses. Its global extent and temporal continuity allow for robust spatiotemporal comparisons at national and regional levels, which align with our objective of characterizing fire patterns across Peru. Although MCD64A1 has been widely validated and applied in global fire studies, it presents known limitations—particularly, in detecting small or understory fires, and in regions with steep topography or frequent cloud cover, such as the Andes as High Rainforest regions. While other datasets provide complementary information, such as burn severity, their integration falls beyond the scope of this study. Future research could incorporate these datasets and consider higher-resolution sources to better detect small-scale fire events and refine assessments of fire impacts.

On the other hand, yearly land covers were obtained from the product MCD12Q1 Collection 6 MODIS Land Cover from 2001 to 2020, also derived from MODIS at a spatial resolution of 500 m (Friedl and Sulla-Menashe 2022). In this study, we used the Cover Type 1 band that refers to the land cover classification using the International Geosphere–Biosphere Program (IGBP) methodology. This product has been widely used for fires and cover change studies in global and tropical areas (Andela et al. 2019; Armenteras et al. 2021). We reclassified the original 17 categories into 7 (Figure 1b; Table S1) based on ecological characteristics and their relevance for national land use and fire analysis: (1) evergreen forests (EFs, 57.24% of national surface at 2001; defined as a forest cover dominated by evergreen trees with canopy > 2 m and tree cover > 60%); (2) deciduous forests (DFs, 0.15%; defined as a forest cover dominated by deciduous trees with canopy > 2 m and tree cover > 60%); (3) shrublands (Sh, 2.88%; defined as areas dominated by woody perennials—1–2 m height—with at least 10% of tree cover); (4) savannas (S, 3.93%; defined as areas with tree cover from 10% to 60% and canopy > 2 m); (5) grasslands (G, 24.81%; defined as areas dominated by herbaceous annuals < 2 m, considering both natural grasslands and pastures); (6) croplands (C, 0.85%; defined as areas where at least 60% of area is cultivated cropland and mosaics of small-scale cultivation 40%–60% with natural tree, shrub, or herbaceous vegetation); and (7) other areas (10.14%; defined as areas such as barren or wetlands).

2.3 | Data Analysis

We conducted a spatial and temporal analysis combining burned area and land cover datasets from 2001 to 2020 to examine fire

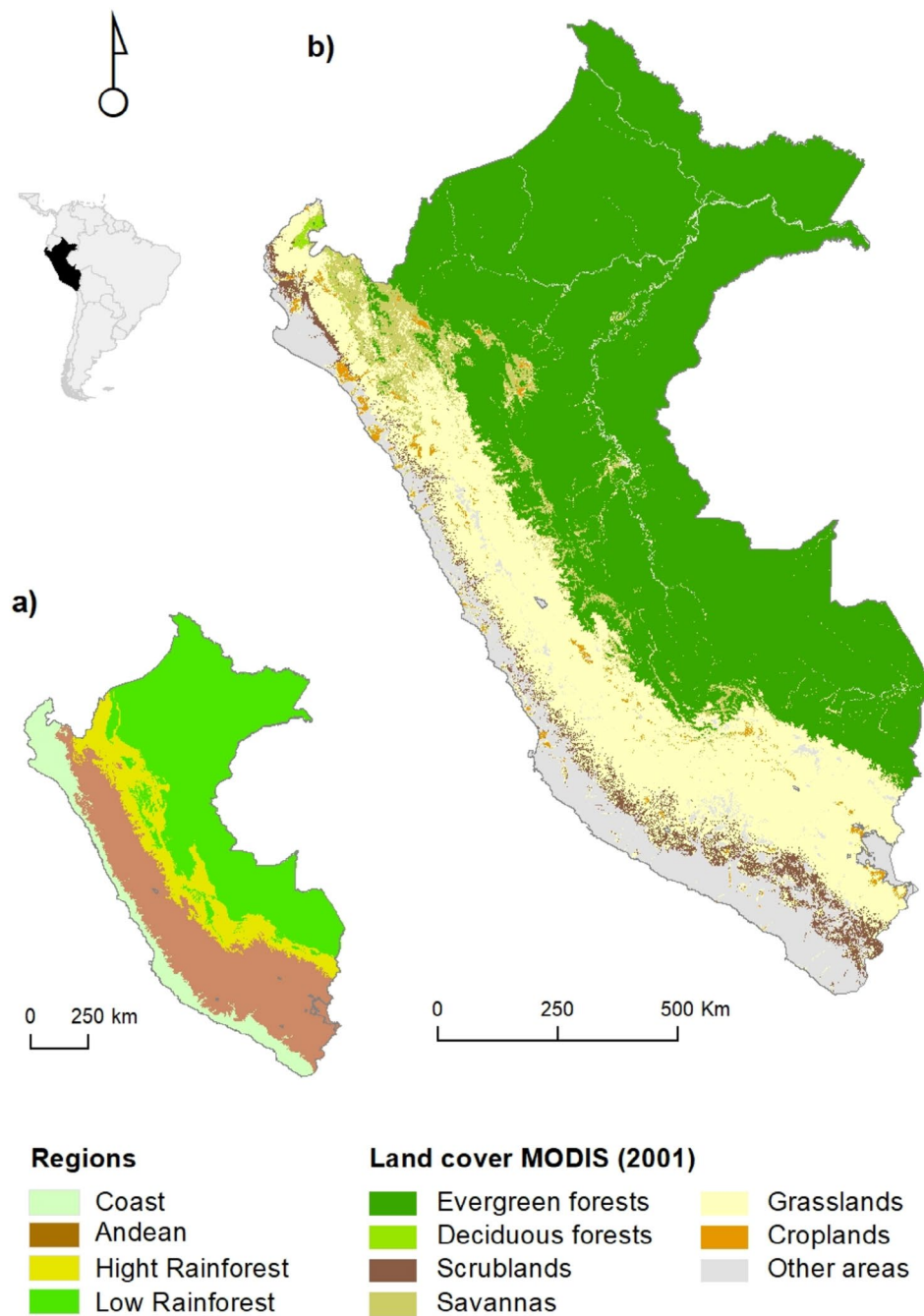


FIGURE 1 | Study area. (a) Peruvian regions. (b) Land covers categories. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ldr.20378)]

patterns, affected land covers, and postfire changes. A total of 1200 and 240 data tiles of monthly burnt area and annual land cover data, respectively, were downloaded and pre-processed to match regions and country boundaries. We calculated monthly from 2001 to 2020 for the whole area and for each region: (1) total burned area detected; (2) number of burned scars; and (3) mean size of burned scars to characterize the spatiotemporal patterns of fire occurrences. We inspected monthly pixel by pixel to identify burned scars, which we hereinafter refer to as “fires” for the purposes of this study. Pixel groups connected for the eight nearest neighbors (considering side and corner) were defined as only one fire. We then calculated the total burned area over the 20-year period for the entire study area and for each region. Additionally, we computed the total burned area

and number of fires annually, as well as the mean annual values and standard deviation of burned areas and fires for the whole study area and by region. We used Spearman correlation to evaluate the relationship between fire number, size, and time (in years) at both national and regional scales.

Combining the two datasets, those of burned areas and land covers, we calculated the annual burned area per land cover type for the 20 years. We also used Spearman correlations to evaluate the change in percentage of forests and shrublands burned through time. Finally, to assess the cover changes of forests and shrublands postfire we quantified their cover change between 2001 to 2020. We used the OpenLand package in RStudio [an intensive quantitative analysis of land use and cover change at

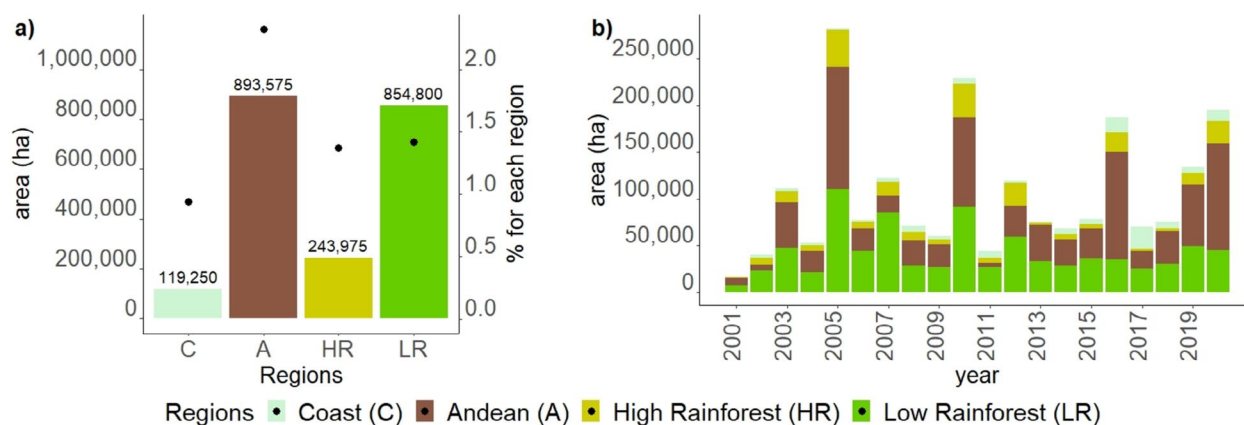


FIGURE 2 | Burned areas (in ha) between 2001 and 2020. (a) Total burned areas per region (bars) and percentage of each region (dots). (b) Annually burned areas per region. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

several time steps based on cross-tabulation matrices, Exavier and Zeilhofer 2020] to examine trajectories of change after fire considering the period 2001–2020, regardless of the number of fires within that period. While this approach allows us to capture broad patterns of change, we acknowledge that future studies should better distinguish between processes of degradation and recovery. To select only forests and shrublands affected by fire after 2001, we sampled pixels that: (i) were forest or shrubland in 2001 (i.e., pixels burned in 2001 were removed) and (ii) were detected as burned area at least one time in the period 2002–2020. We analyzed the datasets using ArcGIS 10.5 (ESRI 2016) and R 4.1.0 software (R CoreTeam 2021).

3 | Results

3.1 | National and Regional Spatiotemporal Patterns of Fires

A total of 2,111,600 ha (1.63% of the whole area of Peru) were detected as burned areas by MODIS between 2001 and 2020, varying by regions: 119,250 ha in the Coast region (0.94% of the region), 893,575 ha in the Andean region (2.32% of the region), 243,975 ha in the High Rainforest region (1.37% of the region), and 854,800 ha in the Low Rainforest region (1.42% of the region) (Figure 2a). The year having the highest burned area was 2005, with 283,250 ha burned (in particular, August 2005 with 121,225 ha, Figure S1), and 2001 was the year having the lowest burned area, with 16,200 ha (Figure 2b). Burned areas in Peru presented substantial variability between years, fluctuating among high values in 2005, 2010, 2016, 2019, and 2020 and years with lower values (Table S2). This pattern was maintained in the regions, except in the Coast region, where the highest burned area was in 2017 (Figure 2b). Additionally, Table 1 presents the mean annual burned area ($\pm$ standard error) in hectares for Peru and each region, allowing a more direct comparison of burned area distribution across regions.

The months with the highest mean burned areas in Peru were August and September, with $33,530 \pm 7303$ ha (mean $\pm$ standard error) and $36,260 \pm 4010$ ha, respectively (Figure S2). These months were maintained in the different regions, except in the Coast region, where the highest value was in October

(954 ± 554 ha), although June and July also maintained great values (909 ± 262 ha and 929 ± 287 ha, respectively, Figure S2 and Table S3).

The years with a great number of fires in Peru correspond to those with great burned areas (Figures 3a and 2b): 2005, 2010, 2012, 2016, and 2020. This pattern was maintained by regions (Figure 3b–e). The year having the highest number of fires was 2005 for the whole area and the Andean, High Rainforest, and Low Rainforest regions (2105, 737, 556, and 860 fires, respectively), and 2016 for the Coast region (92 fires). Furthermore, there was a positive relationship between the number of fires and time in the Coast region ($r=0.61$, $p=0.01$), but the relationships for the whole area and the other regions were non-significant ($p>0.05$ in all cases).

Mean fire size in Peru also presented a strong variability between years (Figure 4; Table S4). There was also a positive significant relationship between mean fire size and time in the Coast ($r=0.57$, $p=0.01$) and Andean regions ($r=0.49$, $p=0.03$), while the relationships for the whole area and the other regions were nonsignificant ($p>0.05$ in all cases). In the whole country, 46% of fires were small (25 ha, one pixel) and 6% had more than 425 ha (Figure 5). The percentage of small fires was similarly high in the High and Low Rainforests regions (54% and 51%, respectively), while in the Andean and Coast regions this percentage of small fires was lower (36% and 34%, respectively). The opposite was found in the case of large fires: in the High and Low Rainforests regions, 3% and 4% of fires, respectively, had more than 425 ha, while this proportion of large fires increased to 10% and 8% of fires, respectively, in the Andean and Coast regions.

3.2 | Burned Land Covers at National and Regional Scale

Most land covers that burned in Peru were grasslands, followed by savannas and forests (Figure 6a). However, this pattern changed within the regions (Figure 6b–e). In the Andes region, the most burned land cover was grasslands; in the Coast region, it was croplands; in the High Rainforest region, it was savannas followed by forests; and in the Low Rainforest, it was forests

TABLE 1 | Mean $\pm$ standard error of annual burned area (ha) between 2001 and 2020 for the whole area of Peru and its different regions.

Year	Peru	Regions			
		Coast	Andean	High rainforest	Low rainforest
2001	1350 $\pm$ 605	0	727 $\pm$ 382	65 $\pm$ 41	558 $\pm$ 299
2002	3377 $\pm$ 1940	281 $\pm$ 122	554 $\pm$ 330	631 $\pm$ 419	1910 $\pm$ 1235
2003	9319 $\pm$ 4576	288 $\pm$ 139	4027 $\pm$ 1483	1029 $\pm$ 670	3975 $\pm$ 3011
2004	4450 $\pm$ 1601	285 $\pm$ 158	1917 $\pm$ 765	498 $\pm$ 241	1750 $\pm$ 867
2005	23,604 $\pm$ 11,299	150 $\pm$ 68	10,894 $\pm$ 5241	3335 $\pm$ 1608	9225 $\pm$ 5795
2006	6427 $\pm$ 3154	140 $\pm$ 100	2042 $\pm$ 1123	600 $\pm$ 258	3646 $\pm$ 2680
2007	10,173 $\pm$ 4503	379 $\pm$ 292	1496 $\pm$ 650	1165 $\pm$ 493	7133 $\pm$ 3918
2008	5929 $\pm$ 3198	508 $\pm$ 297	2267 $\pm$ 1271	769 $\pm$ 389	2385 $\pm$ 1587
2009	4985 $\pm$ 2460	238 $\pm$ 161	2029 $\pm$ 925	479 $\pm$ 229	2240 $\pm$ 1504
2010	19,108 $\pm$ 9833	469 $\pm$ 162	7944 $\pm$ 3717	3038 $\pm$ 1604	7658 $\pm$ 4604
2011	3642 $\pm$ 1597	615 $\pm$ 267	427 $\pm$ 235	379 $\pm$ 227	2221 $\pm$ 1299
2012	9975 $\pm$ 5540	231 $\pm$ 89	2785 $\pm$ 1147	1996 $\pm$ 1281	4963 $\pm$ 3723
2013	6292 $\pm$ 3562	65 $\pm$ 43	3200 $\pm$ 1392	269 $\pm$ 200	2758 $\pm$ 2026
2014	5673 $\pm$ 2966	515 $\pm$ 311	2308 $\pm$ 1398	433 $\pm$ 202	2417 $\pm$ 1693
2015	6521 $\pm$ 3087	419 $\pm$ 222	2738 $\pm$ 1114	402 $\pm$ 199	2963 $\pm$ 2126
2016	15,581 $\pm$ 5793	1317 $\pm$ 452	9617 $\pm$ 4249	1725 $\pm$ 987	2923 $\pm$ 1830
2017	5806 $\pm$ 2114	1946 $\pm$ 915	1585 $\pm$ 478	185 $\pm$ 105	2090 $\pm$ 1332
2018	6302 $\pm$ 3313	631 $\pm$ 292	2885 $\pm$ 1219	233 $\pm$ 141	2552 $\pm$ 2184
2019	11,196 $\pm$ 5681	529 $\pm$ 210	5502 $\pm$ 2536	1058 $\pm$ 650	4106 $\pm$ 2702
2020	16,256 $\pm$ 6381	933 $\pm$ 321	9521 $\pm$ 3718	2042 $\pm$ 1027	3760 $\pm$ 2665

followed by savannas. A total of 513,600 ha (0.66%) of forests and shrublands were burned between 2001 to 2020, distributed by regions: 1850 ha (0.21% of forest and shrublands of the region) in the Coast, 15,325 ha (0.46%) in the Andean, 71,475 ha (0.46%) in the High Rainforest, and 424,950 ha (0.73%) in the Low Rainforest (Figure 6f). There was a negative relationship between the percentage of forests and shrublands burned and time for the whole country ($r = -0.54$, $p = 0.01$; Table S6), while the relationships for the regions were non-significant ($p > 0.05$ in all cases).

3.3 | Forest and Shrubland Cover Changes Postfire

A significant proportion of forests and shrublands burned between 2001 and 2020 were transformed into other land cover categories: 44.3% in Peru, 84.5% in the Coast region, 39.6% in the Andean, 38.6% in the High Rainforest, and 44.8% in the Low Rainforest (Figure 7). Thus, forests and shrublands burned were mostly transformed into savannas (37.4%) and grasslands (6.8%) in 2020. There were some regional variations in these predominant postfire land covers: grasslands in the Coast (72.4%), grasslands (20.9%), and savannas (18.7%) in the Andean, and savannas in the High and Low Rainforest (36.8% and 38.9%, respectively) (Figure 7).

4 | Discussion

4.1 | National Spatiotemporal Fire Pattern and Its Regional Variations

Fire pattern in Peru arises from the intricate interaction between natural (e.g., climate variability, droughts, and vegetation flammability) and anthropogenic drivers, where socio-economic, political, and cultural factors shape fire occurrence, frequency, and spread as happens in other parts of South America (Armenteras et al. 2020; Jones et al. 2022; Souza-Alonso et al. 2022).

Our results reveal distinct fire patterns across Peru's regions from 2001 to 2020. The Andean region had the highest burned area (893,575 ha, 2.32% of the region; Figure 2), this is reasonable due to its and long-standing centuries human influence on fire regimes (Román-Cuesta et al. 2014; Zubieta et al. 2021). Additionally, natural climatic factors, such as increasing droughts, have contributed to higher fire occurrences in recent decades (Zubieta et al. 2021). In contrast, fire activity was lowest in the Coast region, where scarce fuel vegetation and its lower flammability inhibit the ignition and spread of fire (Armenteras et al. 2020). In Amazonia, fires are primarily driven by anthropogenic activities, particularly,

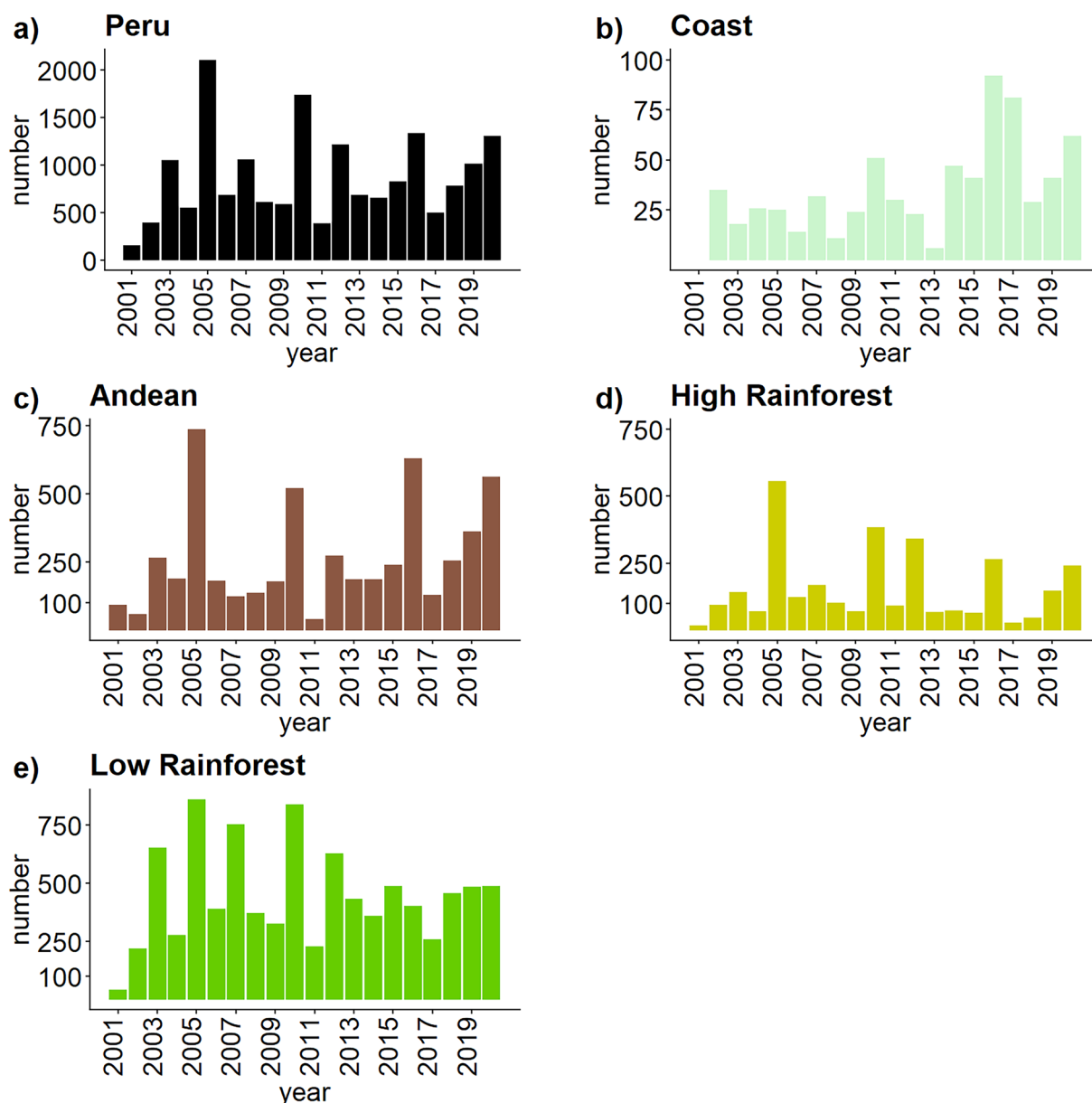


FIGURE 3 | Number of fires detected between 2001 and 2020 for the whole area of Peru and the different regions. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

agricultural expansion, despite the region's traditionally not being prone to burning (Lizundia-Loiola et al. 2020; Lapola et al. 2023). The Low Rainforest recorded considerable burned areas (854,800 ha, 1.42% of the region), whereas fire in surface and number in the High Rainforest region was lower than in the Low Rainforest region, likely due to reduced agricultural-driven deforestation (Móstiga et al. 2024a, 2024b). However, official national fire records, particularly in the Low Rainforest, underestimate these trends by nearly a factor of 30 when compared to our satellite-based observations (SENAMHI-MINAM (Servicio Nacional de Meteorología e Hidrología del Perú- Ministerio del Ambiente del Perú) 2018; Figures S6 and 5).

Seasonal fire trends varied across regions (Figure S2). Fires peaked at the end of the dry season (August–September) in the Andean, High Rainforest, and Low Rainforest regions,

aligning with previous studies (Figure S2; Armenteras et al. 2017; SENAMHI-MINAM (Servicio Nacional de Meteorología e Hidrología del Perú- Ministerio del Ambiente del Perú) 2018; Zubieta 2019). However, the Coast exhibited peak burned areas at the beginning and end of the rainy season (June, July, and October). A potential explanation for this divergence is due to natural fuel accumulation during wet periods (Cuentas Romero and Salazar Toledo 2017).

Interannually, fire activity, burned areas, and the number of fires were notably high in 2005, 2010, 2016, 2019, and 2020 (Figures 3 and 4), with the first 3 years coinciding with El Niño-related droughts, which intensify fire risk in Amazonia (Novoa and Finer 2017; Jimenez et al. 2021; Pontes-Lopes et al. 2021) and in the Andes (Armenteras and Retana 2012; Román-Cuesta et al. 2014; Zubieta 2019; Zubieta et al. 2021). Meanwhile, the increase in fires in 2019 and 2020 aligns with reports of

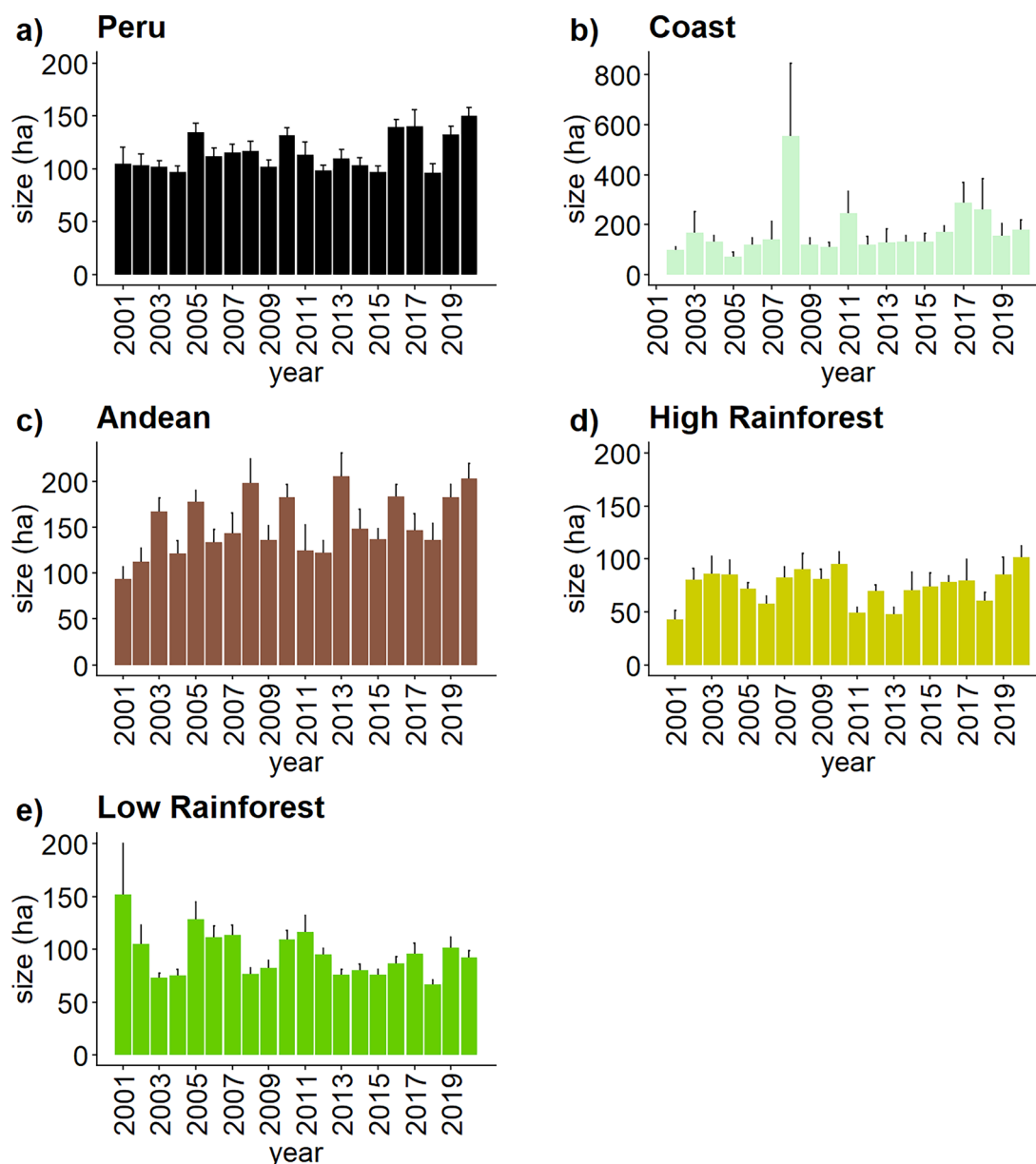


FIGURE 4 | Mean size ± standard error (in ha) of fires detected between 2001 and 2020 for the whole area of Peru and the different regions. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ldr.20373)]

widespread deforestation-driven burning in tropical South America (Novoa and Finer 2017; Cardil et al. 2020; Lizundia-Loiola et al. 2020). In contrast, the Coast showed peak fire years in 2016–2017, linked to a severe drought preceding the 2017 El Niño Costero event (localized ENSO in the north of Peru; Ramírez and Briones 2017), that had profound impacts on the Coast region (Móstiga et al. 2024a). Moreover, our data indicate a rising trend in the number of fires over time in the Coast region, a pattern not mirrored in other regions or the study area at large (Figure 3).

Regarding fire size (Figure 4), no overall increasing trend was observed in Peru or the Low and High Rainforest regions, while a clear rise was detected in the Andean and Coast regions. This trend might be attributed to prolonged droughts (Zubieta 2019; Zubieta et al. 2021). Although 58% of Amazonia remains too humid for fire (Burton et al. 2022),

future warming and drying conditions could heighten fire risk (Burton et al. 2022). Despite the increasing prevalence of megafires (> 10,000 ha) in South America driven by climate change and unsustainable land-use practices (Linley et al. 2022; Armenteras and de la Barrera 2023), Peru did not follow this trend during 2001–2020, with the largest recorded fire reaching 2375 ha in 2018 in the Coast region (Figures 5 and S4). Furthermore, large fires were most frequent in the Andean and Coast regions, despite their fragmented landscapes restricting fire spread (Sylvester et al. 2017; Schröder et al. 2021; Zubieta et al. 2021).

It is important to note that this study does not detect small-scale fires under 25 ha—an inherent limitation of medium-resolution remote sensing products like MCD64A1. While this dataset offers consistent and validated coverage suitable for national and regional fire pattern analyses, smaller fires may

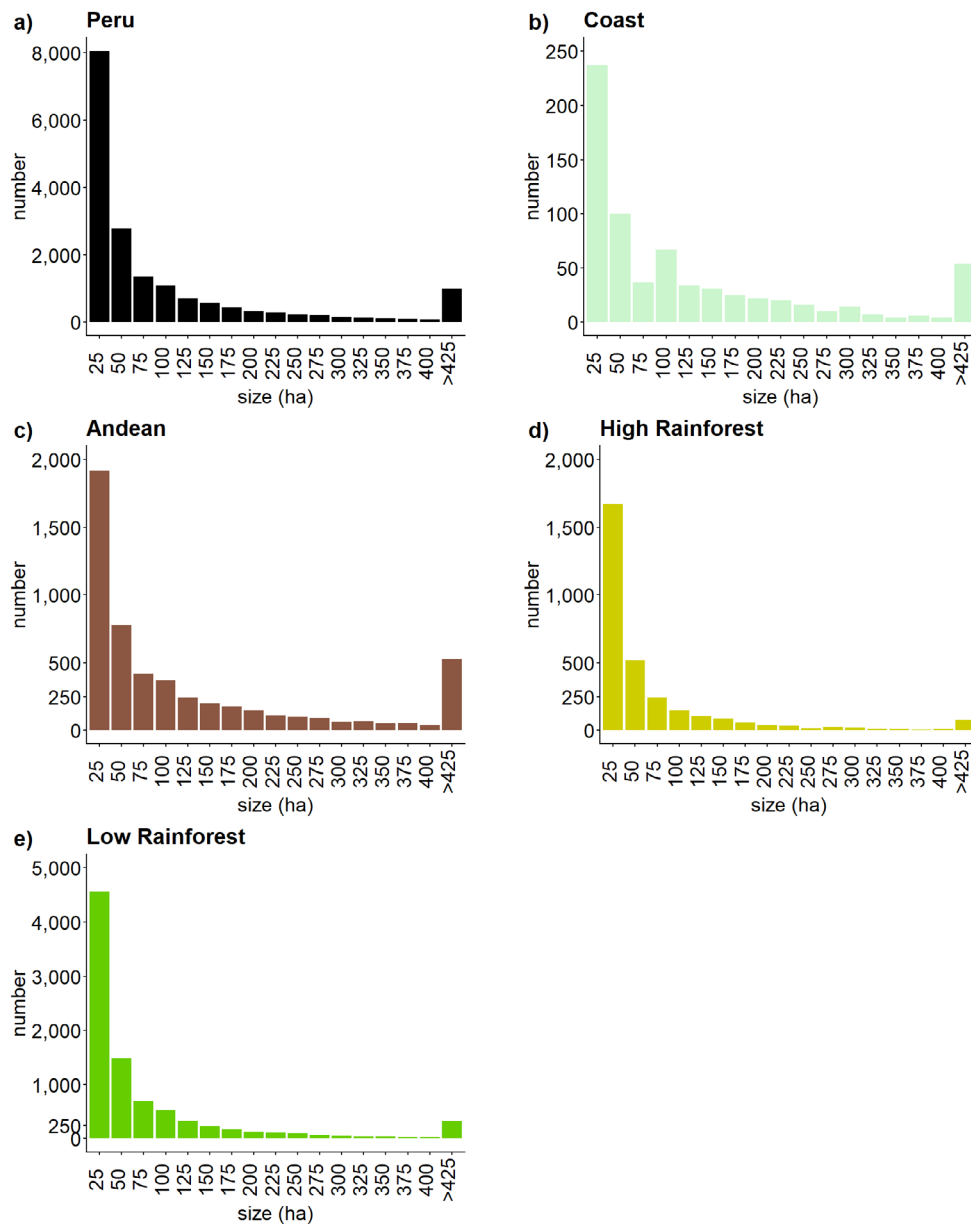


FIGURE 5 | Number of fires by sizes (in ha) between 2001 and 2020 for the whole area of Peru and the different regions. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ldr.2037)]

still have meaningful cumulative ecological effects. Although some evidence suggests that small-scale fires—often associated with shifting agriculture—are not the main drivers of forest loss in Peru, with extensive land conversions playing a more significant role (Ravikumar et al. 2017; Móstiga et al. 2024a, 2024b), their ecological role remains insufficiently understood. Future research could address this gap by combining MODIS with higher-resolution satellite products or field-based validation to better detect and assess the contribution of smaller fires.

Fire-use practices and national regulations also shape fire patterns, particularly in the Coast and Andean regions. Farmers traditionally burn crop residues before planting, and high-altitude grasslands are burned to regenerate pastures. However, since 2008, national legislation (Article 310, Law 29,263) has prohibited burning that harms forest cover,

imposing stricter penalties. Despite this, 98% of fires in Peru remain linked to agriculture and pasture burning (MINAM (Ministerio del Ambiente del Perú) 2023). Limited institutional presence and weak prevention and control programs hinder law enforcement, while the loss of traditional fire knowledge and the absence of community-based fire management further increase wildfire risks, especially under changing climatic conditions. While fire can help manage vegetation and reduce fuel loads (All et al. 2017; Oliver et al. 2017; Hamilton and Salerno 2020), the lack of clear, region-specific guidelines for safe burning and insufficient training have led to widespread mismanagement. Addressing these challenges requires a coordinated fire management strategy at national and regional levels, integrating prevention measures, land-use planning, and policies tailored to local conditions, as well as engaging local communities to better understand their cultural fire practices.

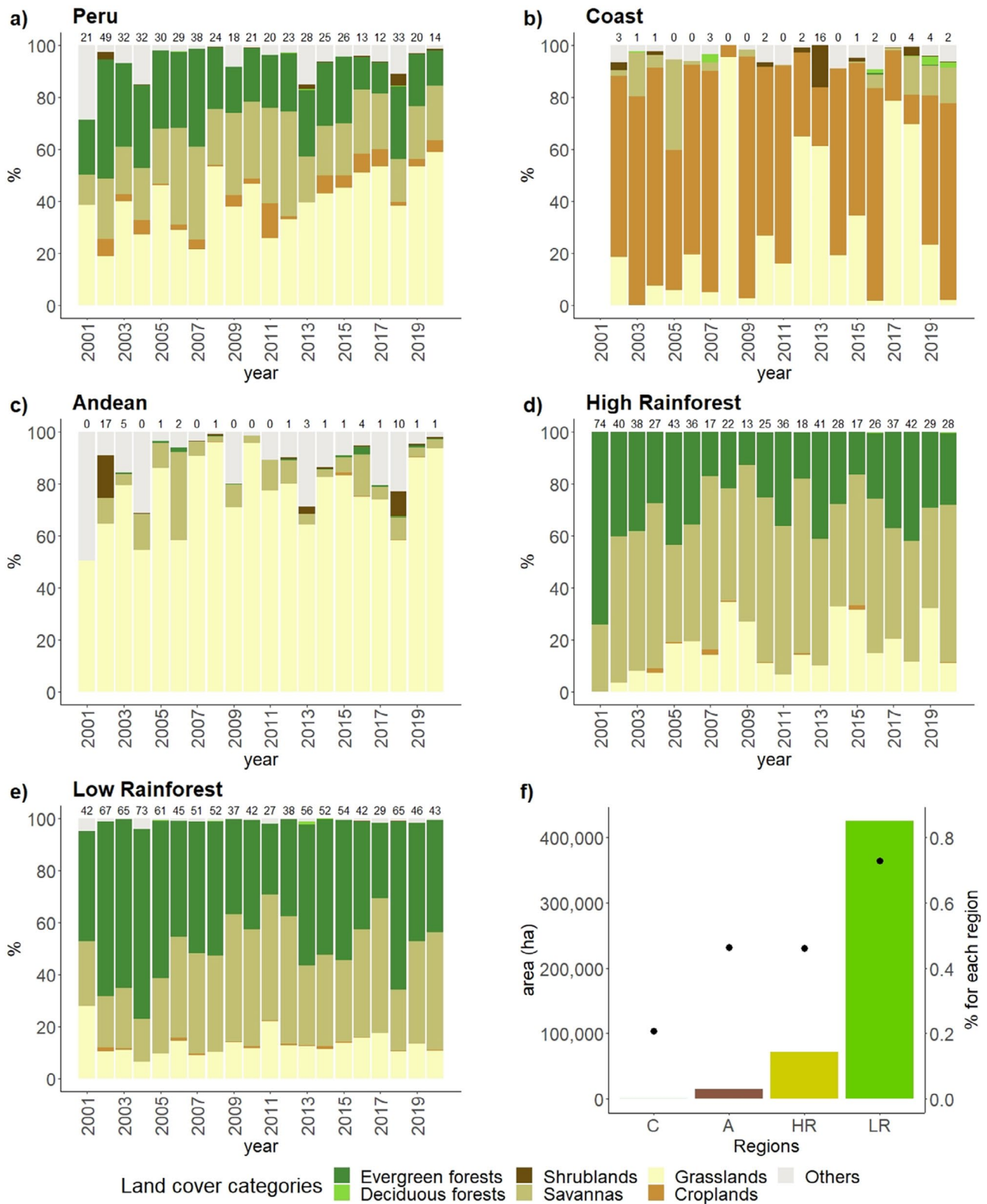


FIGURE 6 | Percentage of the different land covers burned between 2001 and 2020 for the whole area of Peru (a) and the different regions (b–e): Coast (C), Andean (A), High Rainforest (HR), and Low Rainforest (LR). Total burned area of forests and shrublands per region (bars) and percentage of each region (dots) are shown in (f). Numbers above each bar in each (a–e) indicate the percentages of forests and shrublands burned each year. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

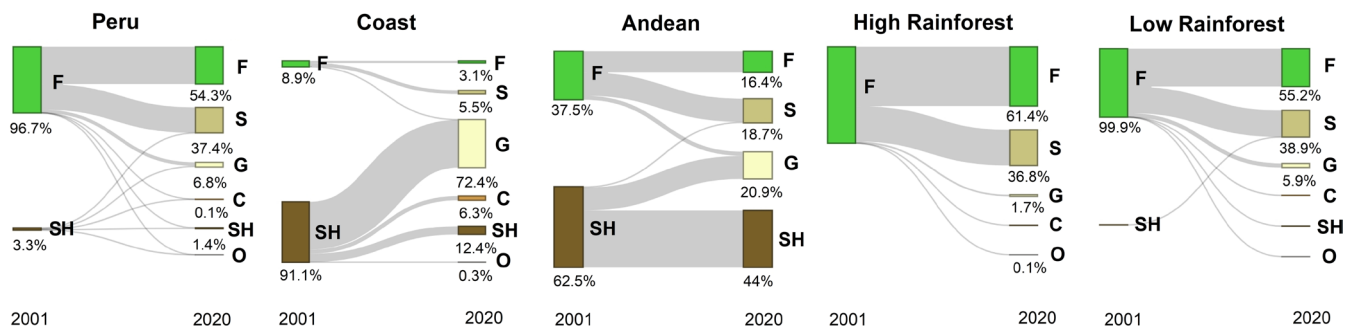


FIGURE 7 | Land cover change of forests and shrublands burned between 2001 and 2020 for the whole area of Peru and its different regions. The proportion of each land cover burned is given, except for very small values. Land cover categories: C croplands, O other areas; F forests (evergreen and deciduous); G grasslands; S savannas; SH shrublands. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

4.2 | Fire Induced Land Cover Change: Trends and Regional Variations

In this study, we demonstrated that over the past 20 years, grasslands were the predominant land cover affected by fires at the national level, followed by savannas and EFs (Figure 6). However, it is crucial to note that the relationship between fire and land cover type is complex. For instance, while grasslands and savannas are fire-dependent ecosystems, EFs typically exist independently of fire (Hardesty et al. 2005; Shlisky et al. 2007). Historically, since the early 1500s, vast grassland areas have been subject to burning, both for land clearing and to maintain productive forage supporting cattle grazing, a significant livelihood source for the local Peruvian population (Oliveras et al. 2018). Some recent studies have reported an uptick in fire frequency in the past decades (All et al. 2017; Oliveras et al. 2018). Consistent with this, we confirmed an increment in the proportion of grasslands burned of at least 25 ha through the last 20 years in Peru, in spite of the current ban legislation (Table S6).

While limited data exist on the influence of fire on forest loss in Peru, it is expected that the increment in deforestation rates could correlate with a changing fire regime in recent times (Novoa and Finer 2017; SERFOR-MIDAGRI (Servicio Nacional Forestal y de Fauna Silvestre—Ministerio de Agricultura y Riego) 2018; Cardil et al. 2020). Contrary to this, our data suggest a decline in the burned area of forests and shrublands of at least 25 ha over the 20 years of study (Table S6). Importantly, regional variations exist: national trends do not always reflect regional patterns (Figure 6; Table S6). In the Andean region, the primary burned land cover is grasslands, historically impacted by cattle raising practices (SERFOR-MIDAGRI (Servicio Nacional Forestal y de Fauna Silvestre—Ministerio de Agricultura y Riego) 2018), as in other Andean locations (Armenteras et al. 2020). In the Coast region, both croplands and grasslands were the most burned land cover (Figure 6). In this region, fires are associated with burns for the preparation of agricultural campaigns and other agricultural practices that also could affect other associated vegetation in spite of the current ban legislation (Cuentas Romero and Salazar Toledo 2017; SERFOR-MIDAGRI (Servicio Nacional Forestal y de Fauna Silvestre—Ministerio de Agricultura y Riego) 2018). In the High and Low Rainforests, land cover categories with some proportion of tree cover, such as forests and savannas, had more burned area than grasslands and croplands (Figure 6). In these regions, fire is used to change land uses

(SERFOR-MIDAGRI (Servicio Nacional Forestal y de Fauna Silvestre—Ministerio de Agricultura y Riego) 2018), due to the high pressure from the agricultural and industrial sectors and/or the development of other legal or illegal activities (Móstiga et al. 2024a), as in other Amazonian locations (Armenteras et al. 2021; Lapola et al. 2023).

4.3 | What Happens to the Burned Forests and Shrublands After 20 Years?

Between 2001 and 2020, nearly half of the burned forests and shrublands in Peru were replaced by savannas, grasslands, and pastures (Figure 7). However, the loss of forests and shrublands due to fire exhibited regional variations: 38.6% in the High Rainforest, 39.6% in the Andean region, 44.8% in the Low Rainforest, and a substantial 84.5% in the Coast region. These variations are driven by both natural factors, such as biophysical conditions and vegetation recovery rates after fire, and anthropogenic drivers, including land use change and accessibility (Figure 7). Furthermore, land use decisions, particularly relating to agro-industries, play a significant role in Peru's forest cover changes, especially in the Rainforest regions (Ravikumar et al. 2017; Glinskis and Gutiérrez-Vélez 2019; Eufemia et al. 2022; Lock and Alexander 2023).

In the High Rainforest region, limiting factors like slope and transport networks curtail human activities, preserving forest cover. Additionally, these forests, rich in fire-tolerant species, often demonstrate quick recovery postfire (Oliveras et al. 2014, 2018). In contrast, the Low Rainforest region has witnessed significant human activities, including agriculture and mining, due to improved transport networks, leading to a greater forest cover transformation. Yet, in both Rainforest regions, the majority of the burned areas convert into savannas, preserving some tree cover, rather than turning into grasslands or croplands (Figure 7).

In the historically settled Andean region, remnants of forests and shrublands are typically found in areas unsuitable for human activities. Fires here predominantly convert forests to savannas, and shrublands to croplands (Figure 7). The Coast region, despite its history of dense human settlement (Portillo-Quintero and Sánchez-Azofeifa 2010), has undergone significant transformation, especially of shrublands, into grasslands.

This is concerning, given the inherent fragility of coastal ecosystems, which are fragmented, slow to recover, and vulnerable to climate change (Portillo-Quintero and Sánchez-Azofeifa 2010; Armenteras et al. 2020; Schröder et al. 2021).

Interestingly, Peruvian forests and shrublands experience relatively infrequent fires: a staggering 96% of the burned forest and shrubland pixels only encountered fire once. Nonetheless, even a single fire can have long-term consequences for Latin American forests, taking them up to three decades to regain their original structure (Oliveras et al. 2018; Zhou et al. 2019; Armenteras et al. 2021). Concerningly, 99% and 60% of the burned areas in the historically intervened Coast and Andean regions, respectively, faced repeated fires over the 20-year period. Given the slow-growth species in these regions, forest recovery remains slow (Portillo-Quintero and Sánchez-Azofeifa 2010; Sylvester et al. 2017; Tito et al. 2022). Furthermore, while forests in the High Rainforest might recover quickly, postfire ecosystems may see a shift in biodiversity, with fire-sensitive species being replaced by more fire-tolerant ones (Oliveras et al. 2018).

Moreover, regarding forest recovery in terms of classification rather than forest structure or diversity, as previously discussed, we acknowledge that early regeneration stages following fires near 2020 in the High and Low Rainforest regions may have been misclassified as grasslands or savannas, introducing a source of uncertainty in our analysis. This highlights the challenges of distinguishing early postfire regrowth from other land cover types in remote sensing-based assessments.

The documented loss of forest and shrubland cover due to fires compromises the potential NCPs and biodiversity delineated in (Móstiga et al. 2023). Even the remaining forested areas might not be spared: secondary forests often take 30–50 years to match the ecosystem services of primary forests, varying by region (Giorgis et al. 2021; Tito et al. 2022). Moreover, these secondary forests are more susceptible to climate extremes, like droughts, which further elevate their fire vulnerability (Hirota et al. 2011; Uriarte et al. 2016). Therefore, in accordance with Armenteras and de la Barrera (2023), safeguarding ecosystems is imperative and this involves: (1) embracing sustainable land-use practices like agroforestry, silvopastoral systems, cultural burning, and green firebreaks; (2) incorporating monitoring and early participatory fire detection systems; and (3) addressing policy and legislative barriers grounded in a comprehensive understanding of fire dynamics.

Altogether, the findings of this study can inform fire management planning, guide territorial and restoration policies, and support community-based fire governance and adaptation strategies, particularly in fire-prone regions where local action and national coordination are both urgently needed.

5 | Conclusion

This study examined how fire occurrences in Peru vary across time and regions, which land covers are most affected, and what postfire changes occur in forests and shrublands. Between 2001 and 2020, we found strong regional variation in burn area, fire frequency, size, and fire seasonality. These disparities may be

exacerbated by global climate change, amplified human activities, and the implementation of unsuitable fire and land cover regulations. Grasslands, savannas, and EFs were the most fire-affected land covers, and many burned areas showed long-term transitions toward land covers characterized by decreased tree density, especially in Amazonia, Andes, and Coast regions of Peru. As a consequence, the biodiversity and NCPs linked to forests and shrublands face threats from fire.

By offering a national baseline of fire regimes and postfire land cover trajectories, this study addresses key knowledge gaps in Peru's fire science. It supports future assessments of biodiversity and NCP losses linked to forest degradation. However, it is important to note that the MODIS dataset used here encounters challenges in detecting forest understory and low-severity fires in tropical forests. Moreover, it remains vital to pinpoint the direct and underlying drivers of fires in Peru, accounting for diverse regional environmental, social, and economic contexts.

Our findings underscore the urgent need to strengthen fire governance, improve land-use planning, and advance forest restoration strategies at the national level in Peru. Policy actions should prioritize early warning systems, promote the conservation of both primary and secondary forests, and reduce land cover conversion. These efforts must include region-specific guidelines that integrate traditional fire knowledge and support community-based fire management, particularly in vulnerable ecosystems. Finally, our findings contribute to broader policy dialog and offer a valuable reference for regional cooperation across Andean–Amazonian countries facing similar fire-related challenges.

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Data Availability Statement

The data that support the findings of this study are available in Earth Data at <https://lpdaac.usgs.gov/data/#nav-heading>. These data were derived from the following resources available in the public domain: MCD64A1 Version 6.1 Burned Area product, <https://lpdaac.usgs.gov/products/mcd64a1v061/> MCD12Q1 Collection 6 MODIS Land Cover, <https://lpdaac.usgs.gov/products/mcd12q1v061/>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Burned detected areas by months in ha between 2001 and 2020 for the whole area of Peru and its different regions. **Figure S2:** Burned detected areas in ha by months between 2001 and 2020 for the whole area of Peru and the different regions. **Figure S3:** Number of fires (burned scars) detected monthly between 2001 and 2020 for the whole area of Peru and its different regions. **Figure S4:** Mean size in ha of fires (burned scars) monthly detected between 2001 and 2020 for the whole area of Peru and its different regions. **Table S1:** Mean $\pm$ standard error of annual of burned area from 2001 to 2020 for the whole area of Peru and its different regions. **Table S2:** Mean $\pm$ standard error of annual of burned area from 2001 to 2020 for the whole area of Peru and its different regions. **Table S3:** Mean $\pm$ standard error of monthly burned area (in ha) between 2001 and 2020 for the whole area of Peru and its different regions. **Table S4:** Mean $\pm$ standard error of fire (burned scars) size (in ha) between 2001 and 2020 for the whole area of Peru and its different regions. **Table S5:** Pairwise correlation of the percentage of burned land cover and years. Pairwise correlation values and the significance (i.e., p -value) of the corresponding Spearman's rank correlation test are given. NS: not significant values ($p > 0.05$). **Figure S5:** Land covers burned between 2001 and 2020 for whole area of Peru and its different regions. Land cover categories: C croplands; DF, deciduous forests; EF, evergreen forests; G grasslands; O other areas; S savannas; SH shrublands. **Figure S6:** National records of fire occurrences and ecosystems burned between 2000 and 2020. (a) Number of fires per regions, (b) number of fires per years, and (c) percentage of ecosystems

affected by fire occurrences for the whole area and its different regions. *Source:* MINAM (a, b, and c) and SERFOR (b, 2017–2020). The 32 original ecosystems categories of MINAM were aggregated in 9.