Two decades of active fire data in Huascarán Biosphere Reserve (Peru): patterns and future challenges to prevent wildfires.

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Abstract

Background

The Andes are recognized as center of biocultural and biological diversity that provide multiple ecosystem services threatened by different anthropogenic forces. Here, fires are widely used in agriculture and other traditional activities with the potential to become larger-scale, unmanageable “wildfires” and contribute to the degradation of both ecosystems and human livelihoods. In this study, we assess the temporal and spatial pattern of MODIS and VIIRS Active Fire Data (AFD) and their relationships to 9 environmental conditions and human activities across the three zones of the Huascarán Biosphere Reserve (HBR), Ancash, Peru between 2001 and 2020.

Results

Xeric climatic conditions seem to drive the temporal AFD pattern across and within years in the HBR. Across years, an oscillating increment of active fire alerts was evident, with years 2016 and especially 2020 displaying the highest AFD records of the two decades. Both correspond to years with the lowest mean annual precipitation. Seasonally, AFD also peaked at the end of the dry season (August and September), but AFD continue until late November of 2016 and 2020. The amount of people on the other hand, measured in terms of population and number of rural villages, is the main driver of where AFA occur, increasing along the limits of the Huascarán National Park (HNP) and the Buffer Zone (BZ) and in weakly controlled areas within the park.

Conclusions

We conclude that a combination of both, xeric conditions, and human pressures, seems to interact and produce high numbers of AFD along key Andean ecosystems like *Puna* grasslands and shrublands that are not ecologically adapted to this type of pressures. Land transformation and a limited capacity of control over key areas within the HNP seem to play an important role in where and when wildfires occur. Finally, although 2020 was an arid year, the covid-19 pandemic would have exacerbated the number of AFDs that occurred in the area, demonstrating that the effects of the pandemic go beyond health problems.

Background

The Andes, recognized as center of biocultural and biological endemism, provide multiple ecosystem services threatened by an increasing number of anthropogenic forces (Borsdorf and Stadel 2015). Here, glaciers, mountain forest and peatlands are the main reservoirs of fresh water, regulating key hydrological processes that are especially important during dry seasons as allow the development of important human activities such as agriculture (Cooper et al. 2010; Johansen et al. 2018). However, rising demands

for water, land, food and other resources from local people bring socio-environmental conflicts, that, if not managed and well understood, often lead to degradation of both ecosystems and human livelihoods (Mark et al. 2017; Bax et al. 2019).

Fire is widely used in the Andes for agriculture and other traditional activities (Borsdorf and Stadel 2015a). In agriculture it is used to clear land in a process of burning and rotating land plots to expand or improve land productivity also known as slash-and-burn (Kleinman et al. 1995). It is also used for eliminating secondary vegetation and litter, renewing pastures for livestock, and sometimes for large-scale deforestation for new farming areas (Beck et al. 2008). Traditional uses include extensive burnings in June 24th as part of the festivities of Inti Raymi and the Campesino's day while other traditions aimed to "call" the rain during the end of the dry season (August - September). Yet despite their controlled uses, fires frequently escape and become larger-scale, unmanageable "wildfires" that cause *Puna* pastures, shrublands and native forest loss and degradation with strong impacts on the Andean biodiversity (Gosling et al. 2009; Cierjacks et al. 2010; Laurace et al. 2014; but see Keating 2007).

Fire's magnitude and frequency are closely related to four factors: fuel, climate-weather, ignition agents and people (Flannigan et al. 2009). Fires need enough fuel and continuity in the landscape to spread, at least ~ 30% of the landscape according to Hargrove et al. 2000. Xeric (e.g., warm and dry) conditions like those occurring during droughts also facilitate fires occurrence worldwide whereas other aspects of atmospheric moisture, wind or lightning activity are critical natural ignition agents that shaped landscapes for millions of years until our days (Cary et al. 2006). In the Amazon, for example, a correlation between drought, rising ocean surface temperatures, forest vulnerability and exposure to fires have been identified as main drivers (Cochrane et al. 2009; da Silva et al. 2018). During the Anthropocene however, human activities had played a major triggering role, responsible of multi-scale changes on wildfire events (da Silva Júnior et al. 2019; Edwards et al. 2020). Moreover, current environmental anomalies exacerbated by climate change is also strongly associated with wildfires around the world. For example, the extreme drought caused by the 2015–2016 El Niño Southern Oscillation (ENSO) event was one of the strongest predictors for fires in the Northern Brazilian Amazon (Fonseca et al. 2017) and southeast Australia (Mariani et al. 2016). Hence, these environmental and human factors do not act independently and rather constantly interact, making hard to forecast wildfires events at different scales.

As a result, uncontrolled fire in areas where they are not part of the natural regime is a real threat for multiple ecosystems and biodiversity (Borrelli et al. 2015; MolinaKnapp 2019). In the Andes, natural fires are uncommon as lightnings, which usually ignited natural fires, mostly occur during the wet seasons when most plants, that can serve as fuel, are wet. In response, different alternatives have been proposed to reduce their impact especially in areas of high biodiversity (Young 1997). One alternative was the development of several ecotourism or nature-based tourism initiatives with the intention of providing a more environmentally friendly economic options to local people, providing a "guide" of good practices to reduce their impact on nature. Yet, results are ambiguous and not conclusive as fire used by local people continued independently of these economic activities given that agriculture is a fundamental part of rural livelihoods (Young 1997). A more restrictive alternative is the establishment of Natural Protected Areas

(NPA) where wildfires are legally forbidden and penalized but in practice, some of these efforts are difficult to achieve. Among them, National Parks have the highest level of restriction and therefore, expected to minimize the occurrence in wildfires within their boundaries. However, although this restrictive approach has shown important results in terms of biodiversity conservation, it has been criticized by not incorporating local humans needs and, in some cases, by directly affecting them by, for examples, forced displacements (Kabra 2018). The Man and the Biosphere (MAB) Program from UNESCO, complement the NPS' objective by integrating people's role in the conservation of areas of high biodiversity, aiming to enhance the relationship between people and their environments by using different interdisciplinary approaches (UNESCO 2021). This conservation efforts within Biosphere Reserves are normally structured over three areas: (i) the "Core Area (CA)" that always is a National Park and protects biodiversity, (ii) a "Buffer Zone (BZ)" that surround the core area and local people used for compatible activities and (iii) the "Transition Zone (TZ)" that surrounds the buffer zone and where most local cities are located, fostering socio-cultural and ecologically sustainable economic activities (UNESCO 2021). Today, the World Network of Biosphere Reserves spans over 129 countries with around 257 million of local people living in there.

In this study, we evaluate the relationships of fires, measured in terms of the number of Active Fire Data (AFD), and different environmental conditions and human activities in the three zones of the Huascarán Biosphere Reserve (HBR), Department of Ancash, Peru between 2001 and 2020. Specifically, we aim to (i) describe the temporal and spatial pattern of AFD, (ii) assess their relationships with climatic and human factors, (iii) identifying the most affected ecosystems and (iv) discussing the effectiveness of three conservation initiatives: ecotourism, the establishment of Huascarán National Park (HNP), and the Huascarán Biosphere Reserve (HBR). We hypothesized that while environmental conditions would drive the temporal pattern of AFD across years and seasons, human activities would be the main driver of where AFD occur. We also predict a greater effectivity of Huascarán National Park (HNP) as a tool to conserve one of the main sites of High Andean biodiversity.

Methods

Study area

We carried out the study in the Huascarán Biosphere Reserve (HBR) (Latitude: -9.439056° , Longitude: -77.347048°), located in the Department of Ancash, Peru (Fig. 1a-d). The 340,000 ha of the core zone (CZ) is protected by Huascarán National Park (HNP) since 1975 (Fig. 1b), covering most of Cordillera Blanca which is considered the highest tropical mountain range in the world (2,400–6,768 m asl), and was declared a World Heritage Site by UNESCO in 1985 (Shoobridge 2005; SERNANP 2017). Cordillera Blanca is flanked by two valleys located in the buffer and transition zones (Fig. 1c-d), the Callejón de Huaylas (east) and Los Conchucos (west), where $\sim 728,000$ inhabitants depend on the ecosystem services that glaciers, forests, grasslands, peatlands, and other high Andean ecosystems provide (Shoobridge 2005). Main cities, like Huaraz (118,836 hab. in 2017), are in the transition zone (Fig. 1d). This area also includes part of Cordillera Negra, an ice-free mountain range running parallel to Cordillera Blanca and the coast for

about 180 km and is dominated by a mixture of intermontane shrubby forests and Puna grasslands. HBR is one of the six Biosphere Reserve that currently exist in Peru and has the main objective of conserving the high Andean biodiversity, landscape beauty and key ecosystem services, such as water, to ~ 2,600 populated areas (UNESCO 2021).

The climate across HBR varies with elevation and is locally modified by topography. The mean annual temperature decreases with elevation, but is relatively stable within years at each elevation, albeit with “*helada*” events (drastic drops in temperature for short periods of the day, usually before sunrise) between May and August (Fig. 1e) (Kaser and Georges 1997; SERNANP 2017). In contrast, mean annual precipitation (640–1400 mm) increases with elevation and shows strong seasonality, decreasing sharply between June and August (Fig. 1f) (Kaser and Georges 1997). As a result, primary productivity in different plant communities, such as wetlands, scrublands, and puna grasslands, show strong seasonal variation, although forested areas, being evergreen, remain without apparent changes in their structure or primary productivity (Morales et al. 2018).

In the CZ, native forests are distributed along most glacial valleys oriented from east to west and are surrounded by an open matrix of *puna* grasslands and montane scrub (SERNANP 2017). Between 3,200 to 4,700 m asl, native forests are dominated by *Polylepis albicans* and *P. weberbaueri* (Fig. 1b) while *Gynoxys* spp. dominates bushy areas (Sevillano-Ríos et al. 2017; Morales et al. 2018). As in several Andean places, these forests are usually distributed discontinuously on both slopes of the glacial valleys, avoiding flat areas with water-saturated soils (Kessler 2006). Glaciers usually start at 5,000 m asl and together with lakes, represent ~ 15% of the core area whereas moraines and debris areas where few or no vegetation exist represent another 34%. The BZ and TZ are dominated by a mosaic of agricultural fields (Fig. 1c), scattered towns, and small cities like Huaraz (~ 120,000 inhabitants) (Fig. 1d). At elevations < 3,200 m asl, native forests are dominated by Alder (*Alnus acuminata*), Quishuar (*Buddleia incana*) and Molle (*Schinus molle*); while Eucalyptus (*Eucalyptus globulus*) or Pine (*Pinus radiata*) dominating forest plantations established since the 1970s (Shoobridge 2005). Crop's productions include native and not native Andean food like Potatoes (*Solanum tuberosum*), corn (*Zea mays*), fava beans (*Vicia faba*), wheat (*Triticum* spp.), barley (*Hordeum vulgare*), fruit like peach (*Prunus persica*), chirimoya (*Annona cherimola*), avocado (*Persea americana*), capuli (*Prunus salicifolia*), pacay (*Inga feuillei*), and more recently, blueberry (*Vaccinium* Spp.) and flower production.

Active Fire Data (AFD)

We use AFD from two collections of the NASA Fire Information for Resource Management System Fire Archive (FIRMS-FA). First, from the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 collected by the NASA satellite Terra and provide data from the entire Biosphere Reserve, with a temporal coverage from January 1, 2001 to December 31, 2020 (Giglio and Justice 2015). We also used the Archive's Visible Infrared Imaging Radiometer Suite (VIIRS-S-NPP) data spanning from January 1, 2012 to December 31, 2020 (Vermote et al. 2016). Data collectively provides coverage for both day and nighttime fires. Both MODIS and VIIRS detect fires of near real-time (NRT) at 1 km and 375 m resolution, respectively and in both cases the recorded coordinate represents the center of either ~ 1 km or 375 m

pixel that contain one or more fires. Therefore, the coordinates do not necessary represent that exact location of the fire but rather, that at least one active fire event is present in the extent (LANCE 2021). Multiple points are expected to represent large fires events. Compared with MODIS, VIIRS allows to detect smaller flaming fires and provide a less underestimated depiction of fire presence. For each fire alert, latitude and longitude coordinates, acquisition date, time, and elevation (m asl) were recorded. Because the same fire event could have been detected by both satellites, we excluded MODIS records that overlapped VIIRS in date and location. Each event was then classified according to its location within the core (n = 734), buffer (n = 1,195) or transition (n = 4,275) zone. Processed data was standardized by area (number of AFD /10,000 hectares) to account for differences in extension of each zone, excluding 170,816 ha within the CZ that correspond to inflammable areas like glaciers, lakes or rocks.

Environmental and anthropogenic covariates

We use 9 environmental covariates measured within 1-km diameter from each AFD and from a set sample of 5,000 random points where none fire alerts were reported. This environmental covariables included geographic, land productivity and climatic information. We obtained elevation (m) and land surface slope (degrees) from the 30-m resolution Digital Elevation Model (DEM) provided by the Shuttle Radar Topography Mission (Farr et al. 2007). Net Primary Productivity (NPP), understood as the rate at which energy is stored as biomass by autotrophs through, for example, photosynthesis in plants (Waide et al. 1999), and in our case reflects the amount of biomass on ecosystems, was derivate from the average interannual Normalized Difference Vegetation Index – NDVI expressed as:

$$NDVI = \frac{(Band5 - Band4)}{(Band5 + Band4)}$$

1

where *Band 5* and *Band 4* correspond to the near-infrared and visible red wavelengths Landsat 8 images of 30-m resolution between 2013 and 2020. We used Google Earth Engine (GEE) to analyze and generate this data, filtering those images with more than 25% of cloud cover (Gorelick et al. 2017). We also use the average daily solar irradiation (Wh/m²/day) of the dry season (June - August) between 1986–2010, calculated for each month with the *r.sun* tool in GRASS GIS 7.2.2, incorporating the effects of slopes and shadows from the topographic images of the Shuttle Radar Topography Mission DEM according to the methodology described by Morales et al. 2018. The mean annual temperature (MAT) and mean annual precipitation (MAP) were obtained from WorldClim 2.1, which are derived from monthly spatially interpolated climate data of ~ 1 km² resolution recorded between 1970 and 2000 (Fick et al. 2017). We also include average monthly temperature (AMT) and average monthly precipitation (AMP) from the same source. The first two, MAT and MAP, were used as a proxy of long-term patterns of thermo energy and water available whereas the AMT and AMP characterize the monthly interannual variation and the local climatic seasonality. From the Nacional Service of Meteorology and Hydrology of Peru (SENAMHI), we used the Cumulative Yearly Precipitation Data (mm) collected by the automatic meteorological station of Recuay (Latitude: -9.722315° ; Longitude: -77.456132°, Elevation: 3,431 m asl) in the TZ of the HBR.

Data was available for the two decades except for year 2014. To measure the anthropogenic impact, we used the Human Footprint Index (HFI) (Venter et al. 2016), a 1-km² resolution raster that measure of the overall impact of human activities on the environment measured in 2009. This global index is comprised of eight variables (built environments, population density, artificial night lighting, crop lands, pasture lands, roads, railways, and navigable waters). We also include the number of people and rural villages located across the HBR from the 2007 and 2017 National Surveys conducted by the National Institute of Statistics and Informatics of Peru (INEI).

Analysis

We used basic descriptive statistics to analyze the inter- and intra-annual patterns of AFD from 2001 to 2020 across the three zones of HBR. Across years, we used the Mann-Kendall trend test to assess a significant increase with years. Temporal autocorrelation was tested with Software Past. 4.03 (Hammer et al. 2001). We also assessed AFD occurrence across the different land cover types described to occur according to the Peruvian National Map of Vegetation Cover (MINAM 2015). Finally, we use smoothed LOESS regressions to characterize AFD relationships to each environmental and anthropogenic explanatory covariate. All the analysis were performed in RStudio (R Core Team 2020) and QGIS 2.18 (QGIS Development Team 2019).

Results

Active Fire Alert pattern on time and space

A total of 6182 AFD were recorded across the three zones of the HBR between 2001 and 2020 (Table 1). Most of them occurred in the TZ (68.94%) and BZ (19.27%) and between years 2016–2020 (63.83%). Across the years and zones, an oscillating increment of AFD was evident, showing a significant increasing trend in all but especially in the transition zone (TZ): CZ [$S = 95$, $Z = 3.05$, $p = 0.002$]; BZ [$S = 119$, $Z = 3.83$, $p < 0.001$]; TZ [$S = 133$, $Z = 4.28$, $p < 0.001$]. Years 2005, 2010, 2012, 2016 and 2020 showed stronger peaks usually followed by a sharp decrease during years of higher precipitation (Fig. 2a). Active fire alerts were especially high outside the HNP in 2016 and 2020 but sharply decreased in years 2017 and 2018 when the cumulative yearly precipitations were some of the highest of the decade (Fig. 2a). Moreover, 2016 and 2020 also presented the greater difference in the number of AFD between in- and outside the CZ, with values of 11.04 and 13.2 AFA/10 000 ha in the BZ and TZ for 2016 and 22.03 and 17.95 AFA/10 000 ha for 2020 compared to 7.1 and 10.75 AFA/10 000 ha inside the CZ in both years. Seasonally, AFD principally occurred during the months of August and September which correspond to the end of the dry season (Fig. 2b). Yet, during 2016 and 2020, fires started before (June - July) and continue until late November (Fig. 3). The yearly cumulative patterns also show that year 2020 exhibited 3.6, 4.6 and 3.6 times more active fire alerts than most previous years for the core, buffer, and transition zones respectively (Fig. 3).

Table 1

Raw number of fires alerts among the three zones of Huascarán Biosphere Reserve and the percentage they represent from the total fire alerts in the HBR between 2001 and 2020. Last four columns show the number of small town and populated centers (Villages) and human population according to the national surveys in 2007 and 2017. Data was acquired from the Nacional Institute of Statistics and Informatics (INEI). Pearson r correlation values are showed in Supplementary Figure S1.

Zones	Fires Alerts - Raw (%)				Total Raw (%)	Villages		Population	
	2001– 2005	2006– 2010	2011– 2015	2016– 2020		2007	2017	2007	2017
Core	61 (0.99)	51 (0.82)	220 (3.56)	397 (6.42)	729 (11.79)	80	43	592	219
Buffer	84 (1.36)	60 (0.97)	272 (4.4)	775 (12.54)	1191 (19.27)	533	548	40298	32933
Transition	179 (2.9)	224 (3.62)	1085 (17.55)	2774 (44.87)	4262 (68.94)	2694	2717	359436	370426
Total	324 (5.24)	335 (5.42)	1577 (25.51)	3946 (63.83)	6182 (100 %)	3307	3308	400326	403578

Spatially, AFD were related with the distribution of people (Fig. 4). Within the CZ, fires were less frequent and concentrated to specific areas of the norther (Quebrada Cedros), center (Quebradas Honda and Potaca) and south (Quebrada Yanayacu and Pumashimi) of Cordillera Blanca. The highest concentration occurred along the CZ-BZ boundary where many people live. Indeed, this pattern was highly correlated to the number of people and rural villages present across the three zones of the reserve (Pearson's r coefficient: 0.99, $p < 0.05$; Figure S1). According to the last two national surveys of INEI, 592 and 219 people lived inside the national park (CZ) by 2007 and 2017 respectively while around 40 and 33 thousand people lived in the BZ at these times (Table 1).

Fire and environmental and human relationships

Active fire alerts peaked around 2,800–3,000 m asl to then decreased with elevation (Fig. 5a). This peak roughly coincides with the buffer zone of the HBR whereas a second and a third smaller peaks Along the gradient of primary productivity (NDVI), fire alerts were maximum at NDVI values between 0.1–0.2 which correspond to areas mainly dominated by *Puna* grasslands. In regions with NDVI values between 0.2–0.5, that correspond to bottom valleys with scrubby and forested areas, the number of AFD were slightly lower but relatively constant (Fig. 5b). This trend was corroborated after quantified the number of AFD among landcover types, were *Puna* grassland, shrublands and agricultural fields accounted for 45.92%, 30.27% and 18.2% of them (Table 2).

Table 2

Raw number of fires alerts among the ten land cover types across the three zones of the Huascarán Biosphere Reserve and the percentage they represent from the total fire alerts on each zone between 2001 and 2020.

Land cover type		Years				Total
		2001– 2005	2006– 2010	2011– 2015	2016– 2020	Raw (%)
Core Zone	<i>Puna</i> grassland	43 (5.9)	40 (5.49)	133 (18.24)	232 (31.82)	448 (61.45)
	Moraine and periglacial areas	16 (2.19)	4 (0.55)	51 (7)	46 (6.31)	117 (16.05)
	Shrub lands	0 (0)	4 (0.55)	23 (3.16)	60 (8.23)	87 (11.93)
	Agriculture	0 (0)	2 (0.27)	10 (1.37)	47 (6.45)	59 (8.09)
	<i>Polylepis</i> forest and aliens	2 (0.27)	1 (0.14)	2 (0.27)	3 (0.41)	8 (1.1)
	Jalca	0 (0)	0 (0)	1 (0.14)	7 (0.96)	8 (1.1)
	Peatlands	0 (0)	0 (0)	0 (0)	1 (0.14)	1 (0.14)
	Forest Plantations	0 (0)	0 (0)	0 (0)	1 (0.14)	1 (0.14)
	Total	61 (8.37)	51 (7)	220 (30.18)	397 (54.46)	729 (100%)
Buffer Zone	<i>Puna</i> grassland	59 (4.95)	38 (3.19)	162 (13.6)	344 (28.88)	603 (50.63)
	Shrub lands	12 (1.01)	11 (0.92)	53 (4.45)	209 (17.55)	285 (23.93)
	Agriculture	9 (0.76)	9 (0.76)	52 (4.37)	194 (16.29)	264 (22.17)
	Moraine and periglacial areas	3 (0.25)	2 (0.17)	3 (0.25)	18 (1.51)	26 (2.18)
	Jalca	0 (0)	0 (0)	1 (0.08)	4 (0.34)	5 (0.42)
	Forest Plantations	0 (0)	0 (0)	0 (0.08)	3 (0.17)	3 (0.25)
	Urban zones	0 (0)	0 (0)	1 (0)	2 (0.25)	3 (0.25)
	<i>Polylepis</i> forest and aliens	1 (0.08)	0 (0)	0 (0)	0 (0)	1 (0.08)
	Peatlands	0 (0)	0 (0)	0 (0)	1 (0.08)	1 (0.08)

	Total	84 (0.7)	60 (0.59)	272 (2.53)	775 (4.57)	1191 (100%)
Transition Zone	<i>Puna</i> grassland	103 (2.42)	111 (2.6)	442 (10.37)	1132 (26.56)	1788 (41.95)
	Shrub lands	56 (1.31)	70 (1.64)	422 (9.9)	950 (22.29)	1498 (35.15)
	Agriculture	15 (0.35)	27 (0.63)	198 (4.65)	562 (13.19)	802 (18.82)
	Moraine and periglacial areas	3 (0.07)	5 (0.12)	14 (0.33)	69 (1.62)	91 (2.14)
	Jalca	0 (0)	8 (0.19)	6 (0.14)	44 (1.03)	58 (1.36)
	Peatlands	1 (0.02)	0 (0)	0 (0)	11 (0.26)	12 (0.28)
	<i>Polylepis</i> forest and aliens	0 (0)	0 (0)	3 (0.07)	3 (0.07)	6 (0.14)
	Mining	1 (0.02)	3 (0.07)	0 (0)	1 (0.02)	5 (0.12)
	Lakes	0 (0)	0 (0)	0 (0)	1 (0.02)	1 (0.02)
	Urban zones	0 (0)	0 (0)	0 (0)	1 (0.02)	1 (0.02)
	Total	103 (0.2)	111 (0.22)	442 (0.87)	1132 (2.23)	4262 (100%)

As temperature decrease with elevation, fires were also related with warmer areas where the Mean Annual Temperature (MAT) range between 12–17 C (Fig. 4c). Its relationship with precipitation (MAP) on the other hand, showed two peaks: one with dryer areas where MAP ranges between 250–600 mm and are in the BZ and TZ in the norther part of Callejon de Huaylas and second, related with wetter areas that ranges between 750–850 mm and are located along the glacial valleys and in the central and southern part of Callejon de los Conchucos (Supplementary Information Fig. S2).

The relationship of AFD against solar radiation and terrain slope suggests that fires are more frequent in steep areas (> 30 degrees) independently of the amount of solar radiation. Indeed, the range of solar radiation (~ 4000–5000 Wh/m²/day) where the number of AFD decreases correspond to flatter areas of the glacier valleys (Fig. 5e-f) whereas the northern and southern slopes usually receive higher (> 5000 Wh/m²/day) or lower amounts (< 4000 Wh/m²/day) respectively. Finally, AFD remained highly constant along most part of the HFP index (Fig. 5g) whereas monthly fire alerts decreased with monthly precipitation (Fig. 5h). On the other hand, the number of AFD was negatively related to the cumulative yearly precipitation (Pearson's *r* coefficient: -0.55; *p* = 0.013).

Discussion

We evaluate the extend to which active fires alert in the Huascarán Biosphere Reserve were related to environmental and human population features between 2001 and 2020. The number of fire alerts constantly increased during last years, especially in the buffer zone where most people use fire in agriculture; and reached its maximum in 2020 during the first wave of the global pandemic. A combination of both, xeric conditions, and human pressures, seem to exacerbate fire alerts occurrence along key Andean ecosystems like *Puna* grasslands and shrublands that are not adapted to this type of pressures. Moreover, land transformation and a limited capacity of control over key extensive areas within the National Park seem to play an important role in where and when fires occur. Hence, the effectivity of different conservation initiatives will depend on understanding how climate shapes long term and seasonal xeric condition - including the distribution of biomass that serve as fuel for fire - and how is this related to different human activities principally associated to agricultural practices.

Climate and human determinants of fires in Cordillera Blanca

While climate can provide suitable condition to wildfire to prosper, human activities usually trigger them, especially in areas where fires are not part of the natural systems (Poveda et al. 2020). If AFD in our study site were natural, we should notice their presence during months with greater prevalence of lightnings. However, lightnings occur during the rainy season (Feb - March), when much of the vegetation is wet and still growing. Contrary, our results show that AFD were especially common at the end of the dry season, after vegetation has gone through several months of drought and a larger amount of biomass were generated. Across years, our results shown an increase of AFD during dry periods (e.g. 2016 and 2020) but the reverse in wetter years (e.g. 2017 and 2018); reinforcing the hypothesis that xeric climatic characteristics (e.g. low precipitation) strongly influence fire events in the High Andes of Peru. With exception of 2003, our results agree with a previous study (All et al. 2017) in terms that 2005, 2010, 2012 were years of high fire activity. However, 2016 and 2020 were way more severe in terms of both fires and dryness. Moreover, similar results were observed in other regions of Peru and Bolivia by Roman-Cuesta et al. 2011, 2014; where years of higher fire activity were characterized by very dry periods and low temperatures but the difference that they observed an increase of precipitation the year before fire-peak (Roman-Cuesta et al. 2011, 2014). Overall, our results are supported by findings that claim that climate, including extreme water deficits and El Niño events, are the main driver of fires in different Andes regions (da Silva et al. 2018; da Silva Junior et al. 2019; Edwards et al. 2020; Poveda et al. 2020).

While climate drives the temporal pattern of fires, the spatial distribution of fires seems to be driven by people. In our study site, AFD was highly related to the number of people living on each zone of the HBR (Table 2; Figure S1). We believe that the use of fire in agriculture and in minor proportion, accidental events caused by tourist, are the main underlying factors behind this relationship.

At the end of the dry season, people located in rural areas start to feel the effects of water scarcity and therefore, the traditionally use of fire for land preparation for a new agricultural year start (Moran et al. 2006; Manta et al. 2018). This practice is widely used in the Andes and other agricultural regions and

usually involves the burn of stubble - the set of remains of stems and leaves that remain on the ground after cutting a crop called “rastros” in Spanish-. In many opportunities, however, burning *rastros* can get out of control if it is not well managed, causing severe damages to native forest and other ecosystems. Plotting our results on a map, clearly shows that most AFD within the HNP occur close to the BZ and around the entrance of densely populated glacial valleys (Figs. 1 and 4). According to the HNP office, most wildfires recorded within the HNP started with this type of practice in the BZ, where agricultural activities are a fundamental part of the livelihoods and culture of local people. But what is in the buffer zone that can make “rastros” so difficult to control? The answer could be *Eucalyptus* and *Pines* forest.

It is known that landcover type can define fire intensity and flammability of an area (Paton et al. 2014). As in many parts of the Andes, *Eucalyptus globulus* and *Pinus radiata* represent key exotic species for rural livelihood whereas also reduces human pressure on native forest for logging (Luzar 2007). For several decades, both were extensively planted in the surroundings of the Cordillera Blanca, becoming part of the landscapes of the buffer and transition zones (Byers 2000). However, both have important characteristics that make them good candidates to prosper in fired conditions (Mutch 1970).

Eucalyptus forests are considered “fire-dependent” trees, due to a high natural flammability that allow them to live in balance with fires (Hodgson 1968). One characteristic that increase its flammability is the presence of oils in the leaves, which have low igniting point and required less oxygen than other plants to burn (Webb 1968). Another property is the low rate of decomposition of the litter, caused by the volatility of the oils in the leaves, which produces an accumulation of litter on the ground and leaves it exposed to the periodicity of fires (Agee et al. 1973; Mutch 1970). For Pines on the other hand, Franzese and Raffaele (2017), indicate that in addition to have specific survival adaptations to fire, such as thick bark and self-pruning capacity (Higgins and Richardson 1998), there are two very important factors that would explain the synergistic relationship between pines and fire: (1) serotiny, which is the prolonged storage of seeds in the canopy and is closely related to the responses of trees to recurrent fires (Keeley, 2012; Lamont et al. 1991), and (2) the ability of seedling to invade and prosper in burned and unburned habitats. Therefore, fire seem to be a good facilitator of *Pinus radiata* success in habitats affected by fires, as recruitment would be carried out quicker in burned areas.

Under technical supervision, different practices have been carried out to manage these types of forest, including continuous thinning and prescribed fire in humid conditions to control or eliminate the amount of fuel (litter) accumulated in the understory (Agee et al. 1973). Additionally, the use of controlled fire is also vital, so destructive fires do not occur (Mutch 1970). However, most local people that practice agriculture in HBR do not necessarily follow these practices but conduct the burn of *rastros* quite often. We believe that the monitoring and manage of fires in the buffer and transition zones are fundamental to protect the native biodiversity of HNP. However, this may require set of well planed activities that include environmental education, logistic and personal preparation, and facilities for the ecological restoration of affected areas.

How are wildfires managed in the HBR?

Wildfires in the HBR should be managed in a hierarchical way by different institutions and key actors responsible for specific tasks, including prevention, the response, and restoration (Vallejo and Alloza 2014). However, in practice, the burden falls mainly on the HNP, the park rangers and local people who somehow respond to these events in a rather voluntary way full of conviction. The National Service of Protected Natural Areas (SERNANP) has an organic strategy for the control of wildfires framed in three components: (1) prospective that seeks to understand the causes of these fires, (2) corrective that seeks to prevent them and (3) reactive that it is implemented in response to a wildfire event (SERNANP 2018). On the other hand, the management of fire risk control is framed in the prevention, reduction, preparation, response, estimation, rehabilitation, and restoration of the affected spaces and are implemented by both SERNANP and the National Forest and Wildlife Service. (SERFOR). Currently, the PNH administration is the main responsible for strengthening the response capacities to wildfires that occur in the CZ of the RBH. These include ongoing training for park rangers and the inclusion of local people through the formation of Participatory Vigilance Committees (Comites de Vigilancia Participativa). In the buffer and transition zone, these activities must be part of the goals of various institutions that include SERFOR, Defensa Civil, and municipal and regional governments (see. Gobierno Regional de Ancash 2020, Plan de prevención y reducción del riesgo de desastres ante incendios forestales de la región Ancash 2020–2023). However, these actions do not seem to be sufficient to counteract the misuse of fire that often unleashes wildfires that are harmful to nature and man. According to Manta (2017), there is still a lack of training for key actors, as well as little equipment, and a high turnover of personnel that together prevent an adequate prevention, response, and management of wildfires in the area. We believe that it is necessary to empower good practices in the use of fire, mainly associated with livestock and agricultural practices, as well as to be able to differentiate between destructive and useful fire through controlled and prescribed burns.

The legislation behind the use of wildfire appears to be an aggravating factor for its management in the HBR. Within the HNP, fires are prohibited for several reasons including that they are not part of the high Andean natural systems and can be highly destructive of its biodiversity. However, the legal framework that applies outside the HNP is unclear given basic laws that on one hand allow the use of fire and on the other hand, laws that contravene and prohibit them (e.g. Law 25268, art.5; Law 29763, DS 018- 2015-MINAGRI, DS 021-2015, art. 127,128,137.3 subsection a, b, c; Penal Code of Peru, Art 310). In addition, legal gaps and the lack of updated supranational and national regulations, and the legal bureaucracy mean that environmental processes and charges throughout the entire RBH are filed up to 100%, leaving many criminal behaviors that cause terrible wildfires unpunished (Manríquez and Rascón, 2020). Given this, the establishment of better criteria and goals of environmental protection in the technical part with clear definitions for different types of ecosystems is especially important.

Effectivity of the Huascaran National Park and Biosphere Reserve

Our results clearly shown that, after correcting by the amount of flammable area, the CZ has significantly less occurrence of AFD that the BZ and the TZ, indicating that the protection role of the HNP is being

largely effective. Certainly, there are certain areas constantly affected over the years that we hypothesize is given to logistic difficulties to control remote areas where centers of control are absent. La Quebrada Cedros or the sector between the towns of Chacas and Huari, for example, are poorly patrolled areas with difficult access and it is where most of the AFD are concentrated. This contrasts strongly with areas such as Quebrada Llanganuco or Uta where surveillance is constant, and the number of AFD is almost non-existent (see Fig. 1 and Fig. 4). The areas that make up the ZA and ZT do not have significant differences in the number of AFD, suggesting that the environmental policies for fire prevention and control implemented in these two areas are equally inefficient.

Fires during the 2020

The management of wildfires was especially difficult during 2020, a year where the COVID-19 pandemic not only caused many human losses but forced strict lockdowns that stopped many economic activities, including tourism. In 2020, many management activities of the HNP had to be suspended or modified, including the work with local communities and tourism, which represents the main economic income for many local people. It is certainly possible that this economic paralysis contributed to more people to shift to work the land, having made use of fire to clean unused areas for agriculture and livestock. Nevertheless, our results also show that 2020 had drier conditions that could have contributed to this high fire occurrence. Therefore, the pattern of fire in 2020 could be the result of a combined effect of dry weather conditions and an increased number of people redirecting their efforts to agricultural activities that involved the use of fire. Similar conclusion was made in Colombia, and other part of the globe (Amador-Jimenez et al. 2020).

Conclusions

Our study showed that active fires alerts increased during the last two decades in response to both, xeric conditions during droughts years and the increase of human population in the buffer and transition zones of the HNP. After correcting by area, the core zone has significantly less number of fire alerts than the buffer and transition zone, suggesting a greater effectivity in the control of fires by the Huascarán National Park. However, remote, and not well patrolled areas are frequently affected by wildfires that usually start in the buffer zone. Overall, *Puna* grasslands and shrublands were the most affected ecosystems followed by agricultural zones in the buffer and transition zones. The development of long-term fire management strategy in cooperation with local communities is key to mitigate the negative effects of wildfires in biodiverse mountain systems like the Huascarán Biosphere Reserve.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The datasets used or analyzed during the current study will be made available upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

CSSR and DH: original study design. CSSR: wrote the first manuscript, tables, and figures preparation. CSSR, JM, GT, BM, YL and WM: data collection and curation, statistical analyses. CSSR, BM and WM: wrote different parts of the discussion and manuscript editing. All the authors discussed, read and approved the final manuscript.

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Figures

Figure 1

Huascarán Biosphere Reserve (HBR) (a) protects most of Cordillera Blanca and local people across three zones: the core (b), buffer (c) and transition zone (d). In (a), we also shown main roads, villages, controlled areas (C. Areas), control sites within the HNP. Monthly interannual variation on temperature (e) and precipitation (f) characterize the climatic seasonality along the year. All pictures by CSSR.

Figure 2

a) Biplot of patterns of cumulative yearly precipitation (bars) and active fire alerts (lines) in the three zones of the Huascarán Biosphere Reserve between 2001 and 2020. Fire data is standardized by the area of each zone. Precipitation data (right axes) was not available for 2014 (*). (b) Boxplot of monthly active fire alerts between 2001 and 2020 across the three HBR zones. The shaded area represents the dry season months.

Figure 3

Yearly cumulative pattern of active fire alerts in the three zones of Huascarán Biosphere Reserve between 2001 and 2020. Dashed vertical line represent the cumulative limit of 85% of the years.

Figure 4

Active fire alerts distribution in the three zones of Huascarán Biosphere Reserve between 2001 and 2020.

Figure 5

Local relationships (LOESS) of active fire alerts along the elevation (a), mean interannual primary productivity (b), mean annual temperature (c), mean annual precipitation (d), solar radiation during the dry season (e), land slope (f), and human footprint (Venter et al., 2016) (g) in the Huascarán Biosphere Reserve. Linear relationship (LSR) of the mean number of monthly fire alerts and precipitation.

Supplementary Files

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