

RESEARCH ARTICLE

## FIRE RESPONSE TO LOCAL CLIMATE VARIABILITY: HUASCARÁN NATIONAL PARK, PERU

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### ABSTRACT

In Huascarán National Park (HNP), Peru, grazing and anthropogenic burning have been interacting for decades with natural ignitions and climate variability to reconfigure the fire regimes of the vegetative communities. However, over the last few decades, human alterations to the region's fire regime were perceived by resource managers to have led to an overall increase in fire occurrence and fire extent. Resource managers are now very concerned about the impacts of increasing anthropogenic fires in the National Park because these fires seem to disrupt ecological processes and tourism. To test these beliefs and examine the fire activity from 2002 to 2014, we used a time

### RESUMEN

En el Parque Nacional Huascarán de Perú, el pastoreo y las quemadas antropogénicas han interactuado por décadas con igniciones naturales y la variabilidad climática, para configurar los regímenes de fuego de las comunidades vegetales. Sin embargo durante décadas recientes, las alteraciones humanas en los regímenes de fuegos de la región han sido percibidas por los gestores de recursos como que ha habido un incremento en la ocurrencia y tamaño de los incendios. Estos gestores están ahora preocupados por los impactos del incremento de fuegos antropogénicos en ese Parque Nacional, dado que los mismos parecieran interrumpir procesos ecológicos y afectar el turismo. Para probar esas creencias y examinar la actividad de incendios entre 2002 y 2014, usamos series de tiempo de diferentes productos y

series of several different data products including the MODIS Terra and Aqua platforms (Active Fire and Burned Area) as well as local air temperature and precipitation data. The intra-annual distribution of fires in the HNP and its buffer zone (BZ) showed a consistent increase in the number of active fires and burned areas during the dry season (Peruvian winter). The active fire anomalies showed higher fire activity in the HNP over the period 2002 to 2014. However, burned area anomalies showed consistently higher fire activity in the BZ during the high fire years in 2003, 2005, 2010, and 2014. The spatial distribution of areas burned in the HNP and the BZ from 2002 to 2014 showed that most recurrent burning was inside the BZ, which is in compliance with the HNP's policy but in contradiction with local resource managers' perceptions. Although human activity may influence local fire dynamics, fire responses seemed to be mainly influenced by local climate oscillations. Our results suggest a clear fire response to local climate and, in particular, to precipitation variability. However, it appears that there was a low fire return interval for any given location and that the total area burned for a given year is relatively small. Therefore, small-scale fires created an appearance of larger fire impacts than actually occur within the HNP and its BZ. In this instance, fire perception and fire reality are not aligning and the new challenge for resource managers is how best to reconcile these two factors to more effectively manage the parklands.

datos incluyendo los de la plataforma del MODIS Terra and Aqua (incendios activos y área quemada), y también datos locales de temperatura del aire y precipitación. La distribución intra-anual de incendios en el Parque Nacional Huascarán (HNP) y de su zona buffer (BZ) mostró un incremento consistente en el número de incendios activos y áreas quemadas durante la estación seca (invierno en el Perú). Las anomalías activas de fuegos mostraron mayor actividad en el HNP en el período 2002 al 2014. Sin embargo, las anomalías en el área quemada mostraron incrementos consistentes en la actividad de fuegos en la BZ en los años de alta actividad de incendios en 2003, 2005, 2010, y 2014. La distribución espacial de las áreas quemadas en el HNP y en la BZ desde 2002 hasta 2014 mostró que los incendios más recurrentes fueron dentro de la BZ, lo que está de acuerdo con las políticas del parque, pero que se contradicen con las percepciones de los gestores de recursos. Aunque la actividad humana puede influenciar la dinámica local de los incendios, las respuestas del fuego parecieran estar mayormente influenciadas por las oscilaciones del clima local y, en particular, por la variabilidad en la precipitación. Sin embargo, pareciera que hay un bajo intervalo de retorno del fuego para un lugar en particular, y que el área total quemada en un año en particular es relativamente baja. Por lo tanto, fuegos de pequeña escala crean la apariencia de impactos mayores (causados por grandes incendios) cuando en realidad éstos no ocurren dentro del HNP o la BZ. En este caso, la percepción de la ocurrencia de los incendios y los que en realidad ocurren no concuerdan, y el nuevo desafío para los gestores de recursos es como encontrar la mejor manera de reconciliar estos dos factores para manejar más efectivamente estos parques.

**Keywords:** Andes, climate variability, fire extent, fire occurrence, MODIS, Peru, satellite imagery

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## INTRODUCTION

The Peruvian Andes provide critical ecosystem services for human populations and harbor high levels of biodiversity, including endemic and threatened species. Because of the strong interdependence of human and natural systems, this region is particularly vulnerable to the impacts of climate change and environmental degradation. Deforestation, conversion of land for agricultural uses, and increased grazing pressure have extensively altered high altitude vegetation cover (Byers 2000, Sarmiento and Frolich 2002, Postigo *et al.* 2008, Young 2009). In addition, the Cordillera Blanca (CB) is undergoing rapid changes due to rising temperatures (Vuille *et al.* 2008a, Rabatel *et al.* 2013, Schauwecker *et al.* 2014, Vuille *et al.* 2015) and glacial retreat (Postigo *et al.* 2008, Racoviteanu *et al.* 2008, Silverio and Jaquet 2012, Burns and Nolin 2014). One of the most significant ecological consequences of these changes is a change in fire activity (Román-Cuesta *et al.* 2014).

The response of fire activity to short-term climate variability and human influence is still poorly understood in the CB due to the absence of historical data and ground-based fire references. Consequently, changes at the local level remain to be documented. Our goal was to assess preexisting conceptions and help local Huascarán National Park (HNP), Peru, land managers better understand how the spatial and temporal patterns of local fires and fire regimes have been changing over the last decade in response to both anthropogenic and climatic influences. We offer some insights into the relationship between changes in fire activity, human influence, and local climate variability on fire in the HNP and its buffer zone (BZ) over the period 2002 to 2014. Such improved information could help Park resource managers better manage the parklands into the near future. The main objectives of this research can be summarized as follows: 1) analyze the patterns in fire occurrence, season-

ality, and spatial distribution from 2002 to 2014; and 2) assess the relationships between temperature and precipitation and fire activity.

First, we hypothesized that the HNP experiences higher fire occurrences than the BZ. Secondly, we hypothesized that there has been an increase in the fire frequency and extent over the last decade. Finally, based on previous research, we surmised that fire activity is strongly influenced by local climate variability.

### *Human Drivers and Fire Activity*

In the tropical Andes, anthropogenic fires have been interacting with natural ignitions for millennia to reconfigure the fire regime and population dynamics of the vegetation communities (Byers 2000, Young and Lipton 2006, DiPasquale *et al.* 2008, Young 2009). In the Peruvian Andes, Paduano *et al.* (2003) found low abundances of local and regional charcoal in the sediments of Lake Titicaca at *circa* 17700 yr BP. Bush *et al.* (2005) reported a progressive increase in pollen concentration and charcoal between *circa* 15000 yr BP and 11000 yr BP that corresponds to an increase in vegetative cover and biomass. They also reported a sharp increase in charcoal abundance *circa* 3500 yr BP (mid to late Holocene) that corresponds with archaeological evidence of expanding human presence in the area. Increased anthropogenic disturbance and major influx of larger charcoal fragments are reported throughout the Andes during the late Holocene (since *circa* 1200 yr BP; Chepstow-Lusty *et al.* 1998, Bush *et al.* 2005, Villota and Behling 2014). Humans influence fire regimes (spread, intensity and severity, number and spatial and temporal patterns of fires) by modifying key variables (e.g., fuel type, fuel structure and continuity, ignition, etc.) that affect fire activity (Bowman *et al.* 2011). Ignition sources, for example, tend to increase drastically in human-altered landscapes (Cochrane and Laurance 2008), and anthropogenic fires are a major cause of increased fire incidence in

the tropical Andes (Román-Cuesta *et al.* 2004, Román-Cuesta *et al.* 2011). In the Peruvian Andes, natural fires are often ignited by lightning strikes and occur mainly in the rainy season when the storms are usually associated with heavy rains (Manta Nolasco and León 2004). However, much controlled burning and extensive fires are due to livestock owners who ignite fires all year long, especially during the dry season, to eliminate dry biomass and improve grass regrowth for the following year (Sarmiento and Frolich 2002).

#### *Climate Change and Local Climate Variability*

Paleoecological and paleoenvironmental studies show that fire activity has varied globally and continuously in response to global and regional climatic fluctuations (Weng *et al.* 2004, Power *et al.* 2008, Marlon *et al.* 2009, Villota and Behling 2014). However, few studies have explored the recent changes in fire activity (increases or decreases) in the tropical Andes and their connection to climate change and local climate oscillations (Román-Cuesta *et al.* 2014).

The average global surface temperature has increased by 0.85°C over the period 1880 to 2012 (Hewitson *et al.* 2014). Analysis of near-surface temperature records from 279 stations in the tropical Andes (Ecuador, Peru, Bolivia) for the period 1930 to 2006 revealed a consistent increase after the mid 1970s, with an average warming of 0.10°C per decade over the last 70 years, and an overall temperature increase of 0.68°C since 1939 (Vuille *et al.* 2008a). In the CB, the average air temperature has increased by 0.31°C per decade between 1969 and 1998 but the recent rate has decelerated at over 100 observation stations to 0.13°C per decade over the period 1983 to 2012 (Schauwecker *et al.* 2014). Schauwecker *et al.* (2014) point out that the increase of air temperature in the last 30 years is dominant in the dry season (JJA [July through August] and SON [September through November]).

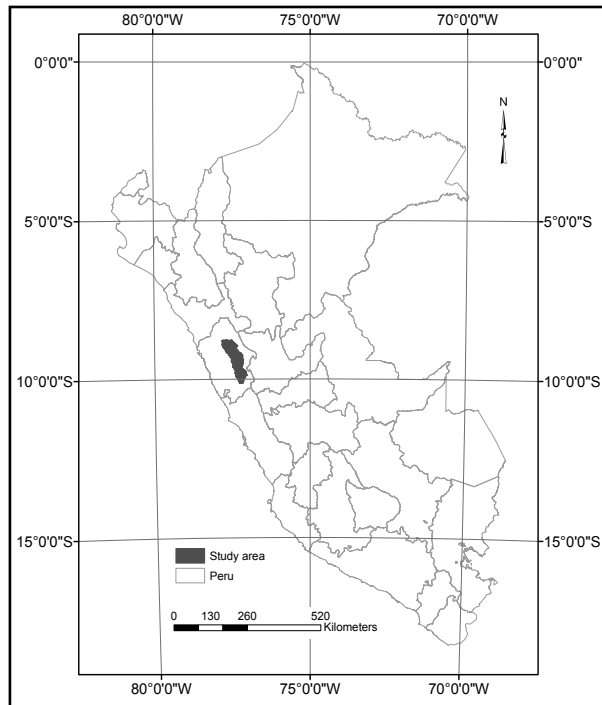
Due to the large spatial variability, no distinct long-term trends in precipitation have been observed on a regional scale for the tropical Andes (Vuille *et al.* 2003). However, Schauwecker *et al.* (2014) found a strong increase in precipitation during the wet and transition seasons (SON, DJF [December through February], and MAM [March through May]) in the CB over the last 30 years (60 mm decade<sup>-1</sup> between 1983 and 2012; Schauwecker *et al.* 2014). This increase is due to stronger easterly winds that facilitate the advection of moist air from the Amazon basin (Schauwecker *et al.* 2014). Consequently, changes in fire activity because of warmer or wetter conditions are likely to occur in the CB. Román-Cuesta *et al.* (2014) showed a synchronous fire response to climate forcing in Ecuador, Peru, and Bolivia. More importantly, their results indicated a clear climate influence, not a human-driven influence, on fire activity both in the dry and wet seasons, and that fuel build-up did not play a significant role.

## **METHODS**

### *Study Area*

Huascarán National Park is located in the Cordillera Blanca range within the Department of Ancash, Peru (8°08'S to 9°58'S and 77°00'W to 77°52'W; Figure 1). The Park (340 000 ha) was established in 1975; accepted as a United Nations Educational, Scientific, and Cultural Organization (UNESCO) Biosphere Reserve in 1977; and designated as a UNESCO World Heritage site in 1985. The BZ covers an area of approximately 170 000 ha. The 1990 Master Plan established its limits and the INRENA (Peruvian National Institute of Natural Resources) made its description official in 2001 (see the document Chief Resolution 317–2001; Shooobridge 2005). The CB is the highest tropical mountain range in the world and is home to over 17 peaks higher than 6000 m above sea level, 80 glaciers, 120 glacial lakes, and a





**Figure 1.** Site location in the Cordillera Blanca, Peru.

number of hot springs (UNESCO 2014). The CB is also the largest glaciated area in the tropics (Morales Arnao and Hastenrath 1999). The diversity of its flora and fauna, and its ecological and geological characteristics within tropical latitudes, make this region especially unique.

The Andes Mountains have a cool to cold climate with rainy summers (austral summer) and very dry winters (Garreaud 1999, Pidwirny 2011). Precipitation in the CB is associated with the intensification of the South American summer monsoon (Garreaud *et al.* 2009), with average values of 770 mm yr<sup>-1</sup> in the northern portions of the park, and 470 mm yr<sup>-1</sup> in the southern valleys. The wet season occurs during the spring and summer (October to March) and usually peaks between February and March, whereas the April to September (fall and winter) part of the year is generally characterized by very dry conditions. The wet season brings 70% to 80% of the annual precipitation (Kaser *et al.* 1990, Kaser and Georges 1997). Generally, relatively cool years in

the Cordillera Blanca are wetter than normal, while relatively warm years are drier than normal (Vuille *et al.* 2008a). Precipitation in the Cordillera Blanca originates primarily from very humid Amazonian air masses, and the hygrometric seasonality is due to the seasonal influence of the South American monsoon. There is no marked thermal seasonality. Temperature is inversely proportional to the altitude, varying from temperate (annual average of 18°C) in the valleys to frigid (annual average below 0°C) in the highest elevations (Pidwirny 2011).

### Fire Data Sources

We used satellite-based fire datasets due to the lack of local ground-based fire references in the CB (Table 1). We chose both the National Aeronautics and Space Administration's Moderate Resolution Imaging Spectrometer (MODIS) Active Fire detections (MYD14A2) and MODIS Burned Area locations (MCD45A1) to assess the seasonal fire frequency and annual fire patterns in HNP and its BZ between 2002 and 2014. The MODIS active fire MYD14A2 uses a contextual algorithm (Giglio *et al.* 2006a) that exploits the strong emission of mid-infrared radiation from fires (Mason and Dozier 1981). The under-representation of fires may occur because of the size of the fires (too small) or the lack of time overlap between the satellite overpass and the fires. Fire visibility might also be affected by persistent cloud cover, dense smoke, or canopy cover (Roy *et al.* 2002). Giglio *et al.* (2006b) added that, although the "fire count" product captures many aspects of the spatial distribution and seasonality of burning, it is difficult to relate it to actual area burned due to the variability in fuel conditions and the differences in fire behavior.

The MODIS burned area product MCD45A1, generated from 500 m MODIS cloud-free reflectance time series data, uses a different algorithm that relies on change in surface reflectance and a static wavelength threshold

**Table 1.** Summary of the selected fire products and climatologic data.

Data	Data type	Data source	Data time span	Spatial resolution	Temporal resolution
Fire products	MODIS active fires (MYD14A2) Level 3	Reverb: <a href="https://reverb.echo.nasa.gov">https://reverb.echo.nasa.gov</a> (Justice <i>et al.</i> 2002, Morissette <i>et al.</i> 2005, Giglio <i>et al.</i> 2006a)	Jan 2002 to Dec 2014	1 km × 1 km	8-day composite
	MODIS burned area (MCD45A1) Level 3	Reverb: <a href="https://reverb.echo.nasa.gov">https://reverb.echo.nasa.gov</a> (Roy <i>et al.</i> 2008, Roy and Boschetti 2009, Boschetti <i>et al.</i> 2013)	Jan 2002 to Dec 2014	500 m	Monthly
Climate data	Temperature (°C) Precipitation (mm)	Simone Schauwecker (Meteodat GmbH, University of Zürich, Switzerland) and National Meteorological and Hydrological Service of Peru. Recuay Station (3404 m)	Jan 2002 to Dec 2012	Local	Monthly

(Roy *et al.* 2005). Studying fires using the coarse 500 m resolution of MODIS fire products is truly a problem in mountainous terrain. MODIS pixels often include 6500 m mountain peaks and 3500 m valley floors, discarding the obscuring effect caused by shadows. However, despite the acknowledged caveats, numerous studies have shown their utility in assessing fire trends at the global scale (Carmona-Moreno *et al.* 2005; Roy *et al.* 2005, Giglio *et al.* 2006b, 2009; Roy and Boschetti 2009; Mouillot *et al.* 2014), the regional scale (Roy and Boschetti 2009, Pricope and Binford 2012, Tsela *et al.* 2014), and in the tropical Andes (Armenteras-Pascual *et al.* 2011, Merino-de-Miguel *et al.* 2011, Román-Cuesta *et al.* 2014).

#### Fire Data Analysis Methods

Our fire datasets included 558 images from the MODIS Active Fire product (.hdf files) and 312 images from the MODIS Burned Area product (Geotiff = Georeferenced Tagged Image File Format).

*Creating data subsets.* We used ERDAS Imagine® (Hexagon Geospatial, Madison, Alabama, USA) to clip the data into area of interest using its Create Subset Tool. We created two subsets using the MODIS Active Fire data (MYD14A2): HNP boundary and HNP BZ

boundary. Similarly, using ArcGIS® 10.2 (ESRI, Redlands, California, USA), we clipped the MODIS Burned Area data with the HNP boundary and HNP BZ boundary. The HNP contained only pixels in the park area, while the initial BZ boundary contained pixels from the Park area and the BZ.

*Building attribute tables for MODIS Active Fire products.* We created attribute tables for each of the new subsets of the Imagine files (.img files) using a batch implementation of the Build Raster Attribute Tables in ArcGIS 10.2 ArcToolbox. This operation attached a .vatdbf file to each of the raster images. The .vatdbf table simply erases all of the values that are equal to zero and displays a condensed cell value table of the raster image. The MODIS Active Fire products contain an active fire mask that identifies fires and other relevant pixels (e.g., cloud). In it, individual 1 km pixels are assigned one of nine classes (Giglio 2010). A value of 7 to 9 indicates fire occurrence and the level of confidence at which it occurs (Giglio 2010).

*MODIS Active Fire product geoprocessing method.* To avoid manually viewing the attribute table for each image and typing the three fire cell values into another spread sheet, a geoprocessing model was created using ArcGIS® Model Builder to automate this process.

The geoprocessing model counted the three fire cell values (7, 8, and 9) and extracted the Julian calendar date associated with each image file name and attached it to the output table. This allowed the temporal data for each file to be maintained. The final product was a table including the meaningful cell value counts with their Julian date attached. We ran this model on each of the two data subsets and hence subtracted the HNP values from the BZ values to get the actual number of fire cells occurring in the BZ. Until this point, the BZ values had included the HNP values. Once the HNP values were subtracted, counts for the BZ and the HNP were independently available and could be used to observe and compare their individual trends.

*MODIS Burned Area product geoprocessing method.* A Geotiff version of the MCD45 burned area product is derived from the standard MCD45A1 .hdf version by University of Maryland (Boschetti *et al.* 2013). This product does not include any overlap between consecutive months and gives information regarding year and Julian day, spatial extent (Win05 and Win 06 for our study area) and quality assessment (Burned Area pixel Quality Assessment) of the burned area (recent fires only) for each pixel with information on detection confidence (1 = most confident, 4 = least confident). Likewise, the geoprocessing model counted the burned area pixel values in each attribute table of the data and created a new dataset for each. The model also extracted the Julian date, by year, for each burned area filename and added it to the attribute table as a field.

For both the Burned Area and Active Fire products, we added a “season” field to the total burned pixel attribute table or the cell value counts table to assess the seasonality of burning. We aggregated the seasons as follow: summer (DJF), fall (MAM), winter (JJA), and spring (SON). The dry season (fall and win-

ter) usually runs from April to September, and the wet season occurs during the spring and summer (October to March) and peaks between February and March.

We estimated standardized active fire anomalies and standardized burned area anomalies over the period 2002 to 2014 by modifying the equation created by Román-Cuesta *et al.* (2014):

$$A_{t,j} = \frac{P_{t,j} - M_j}{\sigma_j} \quad , \quad (1)$$

where  $A$  is the annual or monthly active fire or burned area anomaly,  $P$  is the active fire or burned area pixel count,  $M$  is the active fire or burned area mean pixel count,  $t$  represents each year or each month,  $j$  represents each active fire or burned area, and  $\sigma$  is the standard deviation of active fire or burned area.

The standardized fire anomalies were calculated based on the mean for the CB and on the mean for each area separately (HNP and BZ).

### Climate Data

Monthly air temperature and precipitation data for the base station of Recuay (3404 m) were provided by Simone Schauwecker (Meteodat GmbH, University of Zürich, Switzerland) to analyze climate variability in the CB over the period 2002 to 2013. Schauwecker *et al.* (2014) used a unique dataset from the National Meteorological and Hydrological Service of Peru to assess climate trends and glacier retreat in the Cordillera Blanca since the 1960s.

We used the Spearman’s rank correlation coefficient to test the relationship between monthly temperature and precipitation data and fire activity from 2002 to 2013. We focused on the fire season (dry season) and fire months (April to September) and conducted correlation analyses to temperature and precip-

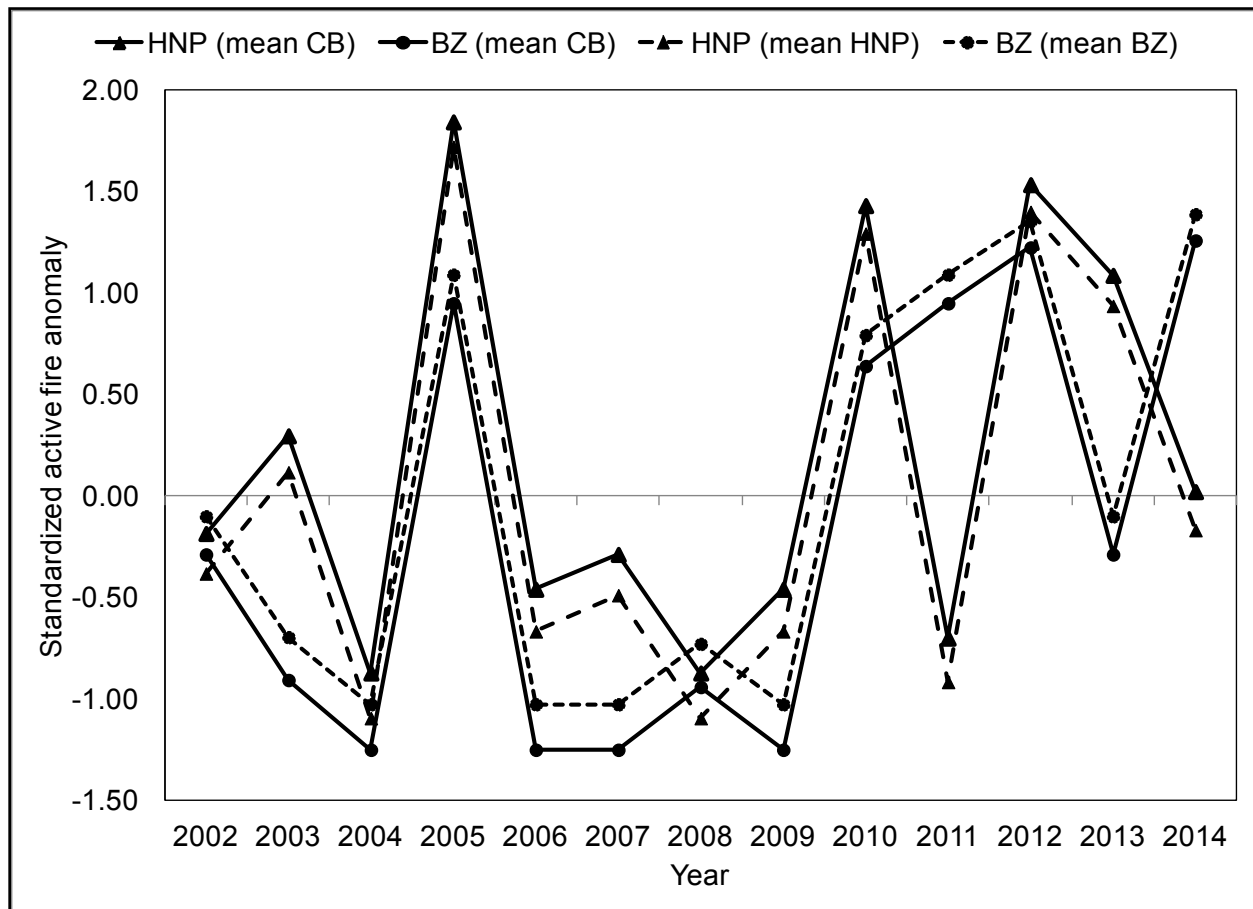
itation data. Our first analysis included all of the months from April to September (i.e., months with fire and months without fire). Our second analysis included only the months showing fire activity (i.e., months with fire only).

## RESULTS

### *Fire Occurrence, Seasonality, and Spatial Distribution from 2002 to 2014*

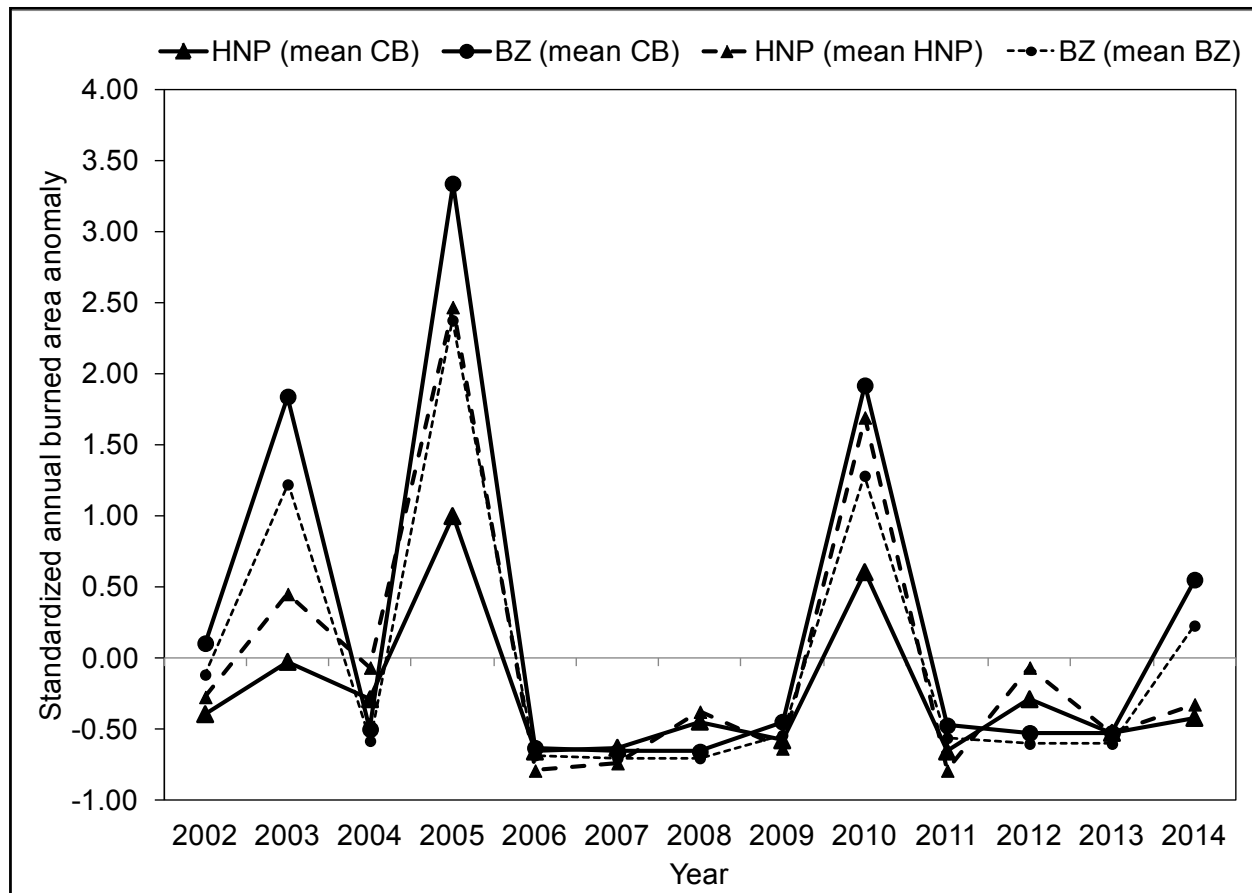
The annual standardized active fire and burned area anomalies for the HNP and the BZ datasets indicated a marked cyclicity, with high fire activity years in 2003, 2005, 2010, 2012, and 2014, and low fire activity years in 2002, 2004, 2006, 2007, 2008, 2009, 2011,

and 2013 (Figures 2 and 3). The active fire anomalies based on the mean for the CB and the mean per area showed a consistent higher fire activity in the HNP over the period 2002 to 2014 except in the years 2008, 2011, and 2014 (Figure 2). Our results for the burned area anomalies based on the mean for the CB showed a consistently higher fire activity in the BZ during the high fire years in 2003, 2005, 2010, and 2014. However, the burned area fire anomalies based on the mean per area had a more complex pattern over the period (Figure 3). The monthly standardized active fire and burned area anomalies aligned well and showed a marked seasonal cyclicity, with higher fire activity during the dry season (JJA; Figure 4).



**Figure 2.** Standardized annual active fire anomalies for the Huascarán National Park (HNP) and the buffer zone (BZ) from 2002 to 2014, Cordillera Blanca, Peru.





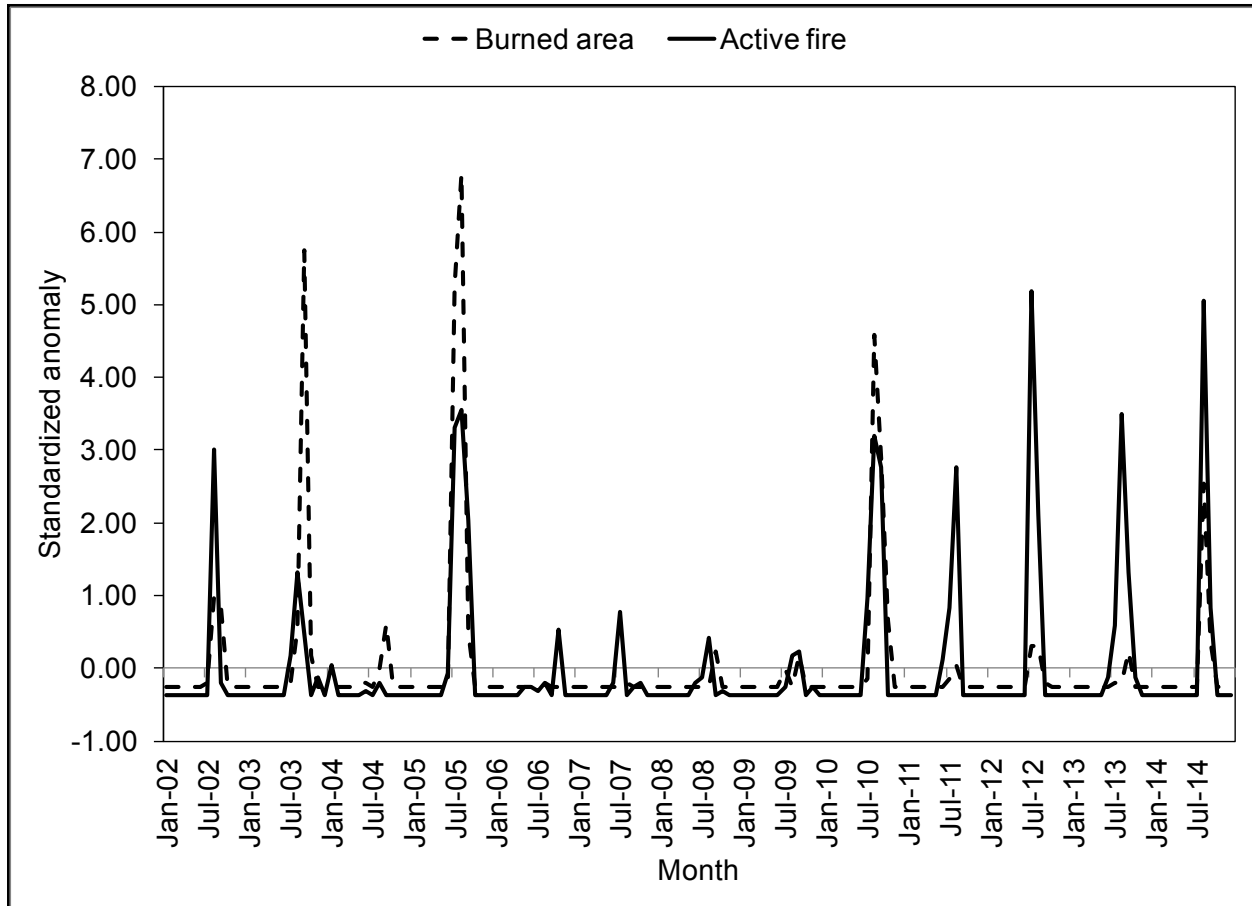
**Figure 3.** Standardized annual burned area anomalies for the Huascarán National Park (HNP) and the buffer zone (BZ) from 2002 to 2014, Cordillera Blanca, Peru.

The intra-annual distribution of fires in the HNP and the BZ showed a consistent peak in the number of active fires (fire counts), with nominal-confidence fire value 8 and high-confidence fire value 9, during the Peruvian winter and the early spring (dry season; Figure 5a). As expected, results from the burned area product aligned well with the results from the active fire dataset. The majority of burned pixels occurred between Julian days 185 and 290; the season with the most burned pixels was winter, with spring being the next highest (Figure 5b).

The spatial distribution of areas burned for the HNP and the BZ from 2002 to 2014 showed the pattern of most recurrent burning inside the BZ, which is in compliance with the HNP policy (Figure 6) but in contradiction

with the local resource managers' observations (Table 2). We found a low fire return interval for any given location as few areas burned more than once during our study time period (Figure 6, grid map E2, E3, E5, E6, F3, and F4). Over the decade, six areas reburned in the following peak fire years: E3 (2005, 2010, and 2014), E5 top left (2003 and 2010), E5 bottom right (2005 and 2014), E6 (2003, 2005, and 2014), F3 (2005, 2010, and 2012), and F4 (2010 and 2014).

Finally, our analysis also showed that, most years, the BZ experiences more area burned than the HNP (Figure 7). If we subtract the glaciated and lake areas (52 762 ha, ANA 2014), between 23 ha and 1363 ha burn (0.14%) on an annual basis inside the HNP (287 238 ha without snow, ice, and lakes), and



**Figure 4.** Standardized monthly active fire (solid line) and burned area (dashed line) anomalies from 2002 to 2014, HNP and BZ, Cordillera Blanca, Peru.

between 23 ha and 3646 ha (0.42 %) inside the BZ (248 638 ha) (Figure 7). The proportion of the total area burned between 2002 and 2014 for both the HNP and the BZ (total CB) was 0.81 % and 2.03 %, respectively.

#### *Effects of Local Climate Variability on Fire Activity during the Dry Season*

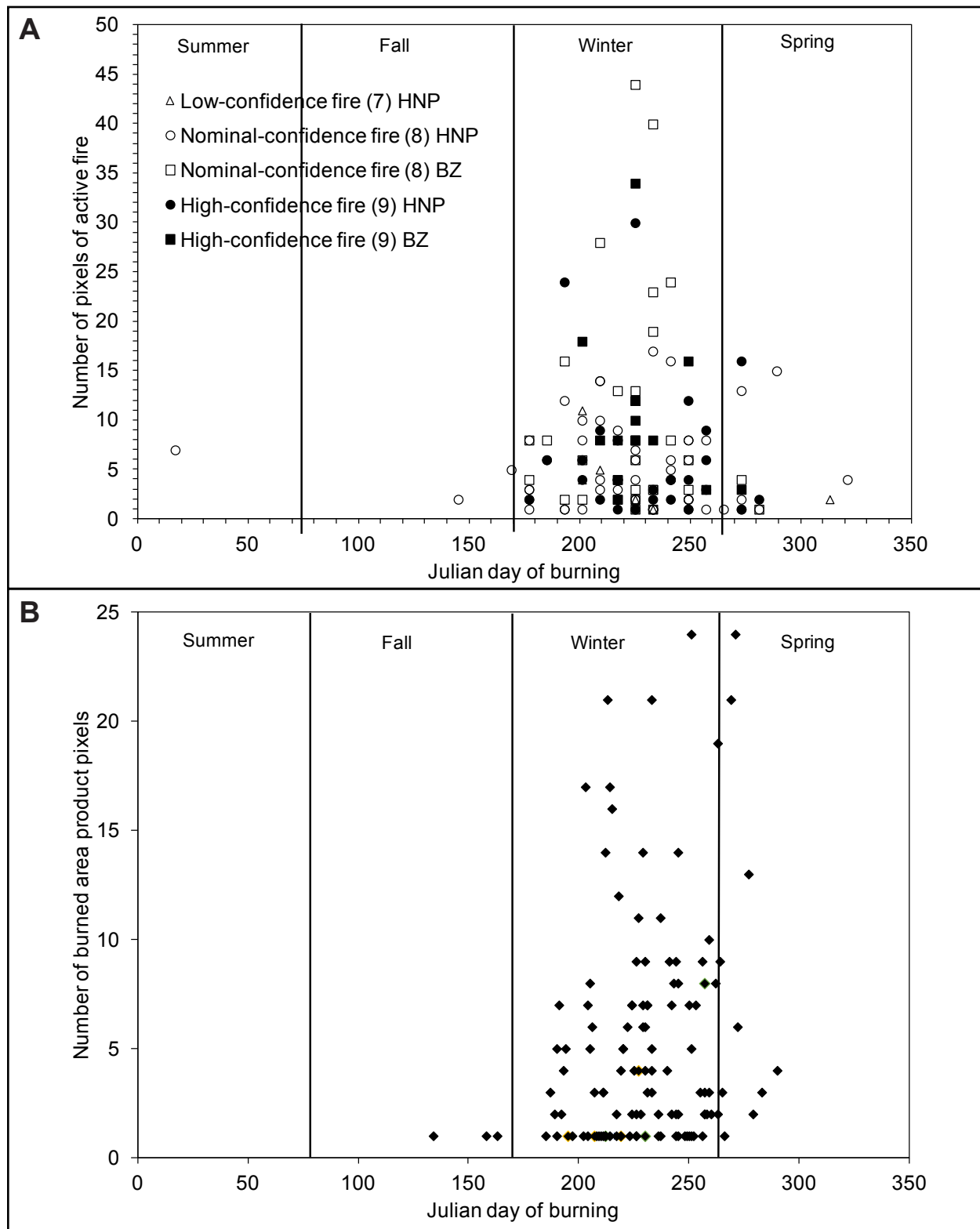
Our first correlation analysis showed a significant negative relationship between temperature and active fire data (Figure 8a). Correlation analyses to determine if precipitation had a major influence on fire activity during the dry season showed significant negative relationships between precipitation and burned areas (Figure 8b), as well as between precipitation and active fire (Figure 8c). To test if

only months in which fire occurred (mostly July to September) responded better to local climate variability during the dry season, we ran a second correlation analysis. Our results showed no significant relationship between climate data and fire activity.

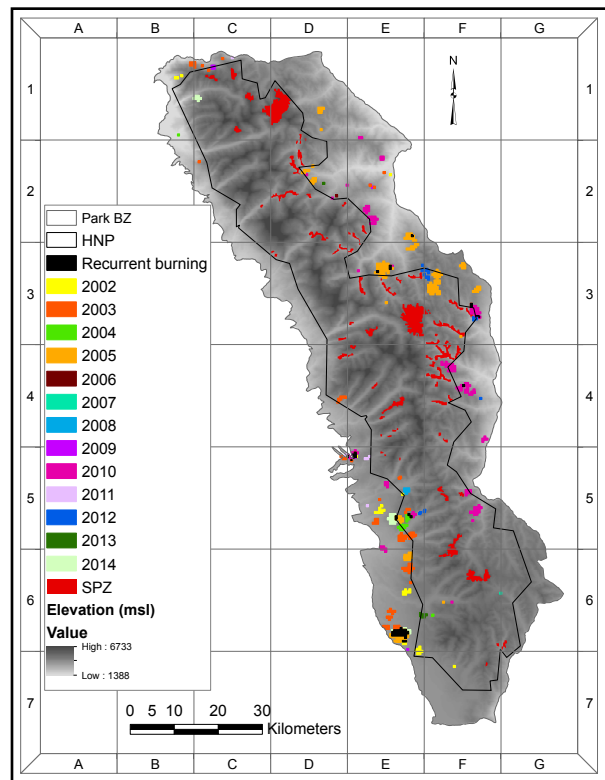
## **DISCUSSION**

### *Fire Trends in Huascarán National Park and Buffer Zone*

Overall, the analysis of the active fire and burned area anomalies for the period 2002 to 2014 for the HNP and the BZ shows a consistent pattern in fire occurrence and seasonality with peak fire activity during the Peruvian winter (dry season), and peaks in burning be-



**Figure 5.** Fire seasonality in the Huascarán National Park and buffer zone, Peru. (A) Number of pixels of active fires by date, season and confidence level (7, 8, and 9); and (B) number of burned area product pixels by date and season (confidence levels 1 to 4). A black diamond (◆) represents one burned area product pixel.

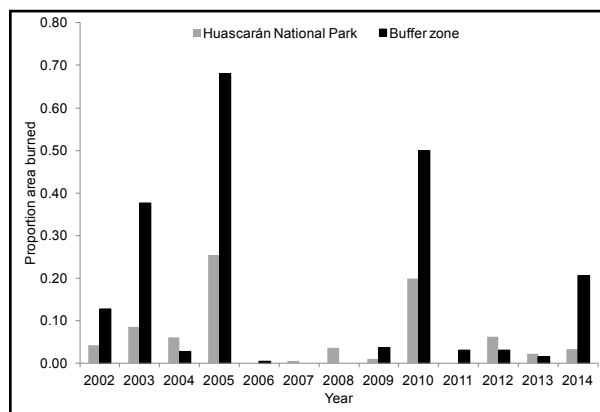


**Figure 6.** Total area burned annually and recurrent burning in the Huascarán National Park and buffer zone, Peru, from 2002 to 2014 based on MODIS MCD45A1 product. The outline of the Digital Elevation Model Clip represents the BZ boundary. The interior line is the boundary of the Huascarán National Park. Few areas burned more than once during our study time period (grid map E2, E3, E5, E6, F3, and F4). Over the decade, six areas re-burned in the following peak fire years: E3 (2005, 2010, and 2014), E5 top left (2003 and 2010), E5 bottom right (2005 and 2014), E6 (2003, 2005, and 2014), F3 (2005, 2010, and 2012), and F4 (2010 and 2014). Sources: Huascarán National Park and buffer zone shapefiles (SERNANP 2014), Strict Protection Zones (SERNANP 2010; grid map B1, C1, D1 to D5, E2 to E5, F3 to F7, and G6), and Digital Elevation Model (Shuttle Radar Topography Mission: US National Geospatial-Intelligence Agency and US National Aeronautics and Space Administration).

tween July and September. These results are consistent with other findings in South America (Carmona-Moreno *et al.* 2005) and the tropical Andes (Bradley and Millington 2006, Armenteras-Pascual *et al.* 2010, Román-Cuesta *et al.* 2014). The active fire anomalies show a consistent higher fire activity in the HNP over the period 2002 to 2014. However, our results concerning the burned area anomalies show a consistently higher fire activity in the BZ during the high fire years in 2003, 2005, 2010, and 2014. The spatial distribution of areas burned between 2002 and 2014 shows the pattern of most recurrent burning was inside the BZ, which is in compliance with the HNP's policy but in contradiction with local resource managers' perceptions. However, some of the areas that burned between 2002 and 2014 were located close to the Park's Strict Protection Zones (SPZ; Figure 6, grid map C1, E3, E5, F3, F4 and F5). In the HNP, the areas zoned for strict protection are spaces in which the ecosystems have been largely or completely undisturbed, or include unique, rare, or fragile species or ecosystems that must be protected from outside influences and require original environmental quality and characteristics for survival. The only activities allowed in these zones are management and environmental monitoring, and, under certain circumstances, scientific research (SERNANP 2010). The SPZs cover 4.76% of the HNP total area. The increase in fire occurrence and the marked seasonality during the Peruvian winter are probably related to fire use. Wildfires that affect forests, native vegetation, and habitats typically begin when herders set fire to grasslands at the end of the dry season to fertilize and promote growth for the following grazing season (Sarmiento and Frolich 2002). The vegetation is dry and extremely sensitive to ignition, and these fires can spread rapidly. Most fires in the tropical Andes are human induced (Román-Cuesta *et al.* 2003, Manta-Nolasco and León 2004, Bradley and Millington 2006, Manta-Nolasco *et al.* 2010, Román-Cuesta *et*

**Table 2.** Number of forest fires in ravines in the buffer zone and the Huascarán National Park between 2005 and 2009. (Data source: translated and modified from SERNANP 2010).

Year	Watershed	Ravine	Origin			Plant community affected
			Months	Buffer zone	HNP	
2005	Yanayacu, Jacabamba, Huaritambo, Pachacoto, Huachesca, Yurma, Wecroncocha, Mullaca, Buin, Ranrahirca, Carhuanga, Juitush	12	April to September	12	9	Grasslands, shrublands and <i>Polylepis</i> Ruiz & Pav. spp. forests, patches of <i>Puya raimondii</i> Harms, rocky slopes with lithophytic plants
2006	Yanayacu, Casca, Quillcay, Ranrahirca-Llanganuco, Huariparmpa, Huachesca	7	May to September	5	2	Native grasslands, shrublands, rocky slopes with lithophytic plants, <i>Polylepis</i> spp. patches
2007	Huachesca, Yanayacu, Casca, Rio Negro, Buin, Mancos	6	June to August	3	2	Grasslands and shrublands and rocky slopes
2008	Casca, Llanganuco, Mancos, Quillcay, Pachacoto, Cutacandra, Rio Negro, Rangracancha, Pucavado, Yanayacu	14	June to December	0	14	Native grasslands, shrublands and <i>Polylepis</i> spp. patches
2009	Jacabamba, Llanganuco, Yanayacu, Rio Negro	4		2	2	Grasslands and shrublands
<b>Total</b>		<b>33</b>		<b>22</b>	<b>29</b>	

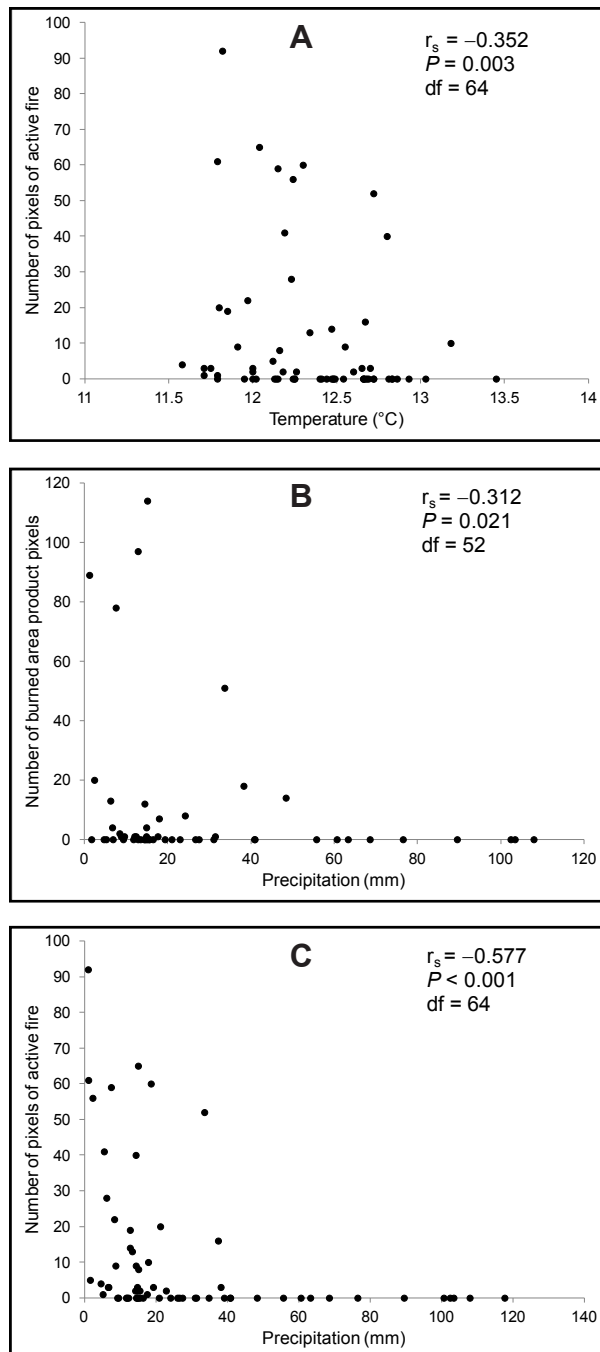


**Figure 7.** Proportion of areas burned in the HNP and BZ between 2002 and 2014, Cordillera Blanca, Peru. Derived from MODIS MCD45A1 product.

al. 2011) and natural ignition may frequently be limited to the rainy season (Young 2009). In Peru and Bolivia, Bradley and Millington (2006) found that the coincidence of persistent cloud cover and low fire occurrences most likely corresponds with the low probability of

fires being set during the wet season rather than clouds obscuring the detection of active fires by sensor. Due to the absence of ground-based fire references, we cannot report missed fire events or areas identified as fire that are not actually fire. The fire size may also be a limiting factor as both MODIS products have size limitations (Giglio *et al.* 2009, Tsela *et al.* 2014). Furthermore, the absence of ignition source data and the low fire return interval for any given location make it difficult to confirm that the fires are human induced, even if some clusters suggest otherwise (Figure 6). Román-Cuesta *et al.* (2014) followed up major fire event locations in the Puna and Paramo over a nine-year period and concluded that, while fire cycles of 4 yr to 6 yr might occur, they are unlikely to correspond to the repeated burning of the same locations. They also concluded that fuel build-up effects exist but should be larger than 9 yr to 12 yr. Although human activity may locally influence fire dy-





**Figure 8.** Scatter plots of (a) number of monthly pixels of active fires versus mean monthly temperature, (b) number of monthly burned area product pixels versus mean monthly precipitation, and (c) number of monthly pixels of active fires versus mean monthly precipitation. Dry season, April to September, including months with fire and months without fire. Spearman's rank correlation ( $r_s$ ),  $P$ -values, and  $df$  are given for each set of points.

namics, Román-Cuesta *et al.* (2014) found that the synchrony and cyclicity of fire responses in the high tropical Andes were mainly influenced by regional climate.

### Fire Response to Local Climate Variability

Numerous studies have reported connections between climate fluctuations and the spatial and temporal behavior in fire activity in South America (Román-Cuesta *et al.* 2003, Carmona-Moreno *et al.* 2005, Bradley and Millington 2006, Armenteras-Pascual *et al.* 2011). In Peru, Román-Cuesta *et al.* (2014) found that Climate clearly influenced fire activity. The confounding factor seems to be the sawtooth pattern of precipitation, which led to an increase of rainfall before the peak fire seasons, followed by drought and unusual low temperature during the fire peak years. Our results align well with their findings and suggest that there is a clear fire response to local climate, and particularly to precipitation variability during the dry season. Román-Cuesta *et al.* (2014) suggested that several particular combinations of temperature and precipitation in the year of the peak and the year immediately before clearly influenced fire activity in the tropical Andes.

## CONCLUSION

While fires continue to be an active part of the ecosystem in the CB, their actual environmental impact is less than the impact currently perceived by local land managers. This is a function of both their proximity to SPZs within the Park and, conversely, to areas highly frequented by tourists. In both cases, Park personnel must address the perception gap and better educate tourists, local herders, and other stakeholder groups. More research is needed to determine the true ecological impact of winter fires on the landscape versus the historical summer fire regime. This would improve Park fire management planning and inform respons-

es. Other potential areas of future study include the fire patterns at higher elevations that are proximate to formerly glaciated areas of the Park. Another critical area of research will be to compare vegetation cover data to fire behavior data to examine both vegetation cover impacts on fire frequency and area burned as well as fire impacts on land cover changes over time. Finally, while we have demonstrated that there is a significant climate component

to fire behavior in the HNP, the short period of record and the high spatial heterogeneity of the landscape and both fire and meteorological patterns require a finer scale, on-the-ground analysis. However, in the HNP, with the active participation of Park personnel, the research presented here can inform resource management and lead to more effective biodiversity and conservation outcomes.

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