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Distant neighbors: recent wildfire patterns of the Madrean Sky Islands of southwestern United States and northwestern Mexico

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Abstract

Background: Information about contemporary fire regimes across the Sky Island mountain ranges of the Madrean Archipelago Ecoregion in the southwestern United States and northern Mexico can provide insight into how historical fire management and land use have influenced fire regimes, and can be used to guide fuels management, ecological restoration, and habitat conservation. To contribute to a better understanding of spatial and temporal patterns of fires in the region relative to environmental and anthropogenic influences, we augmented existing fire perimeter data for the US by mapping wildfires that occurred in the Mexican Sky Islands from 1985 to 2011.

Results: A total of 254 fires were identified across the region: 99 fires in Mexico ($\mu = 3901$ ha, $\sigma = 5066$ ha) and 155 in the US ($\mu = 3808$ ha, $\sigma = 8368$ ha). The Animas, Chiricahua, Huachuca-Patagonia, and Santa Catalina mountains in the US, and El Pinito in Mexico had the highest proportion of total area burned ($>50\%$) relative to Sky Island size. Sky Islands adjacent to the border had the greatest number of fires, and many of these fires were large with complex shapes. Wildfire occurred more often in remote biomes, characterized by evergreen woodlands and conifer forests with cooler, wetter conditions. The five largest fires ($>25,000$ ha) all occurred during twenty-first century droughts (2002 to 2003 and 2011); four of these were in the US and one in Mexico. Overall, high variation in fire shape and size were observed in both wetter and drier years, contributing to landscape heterogeneity across the region.

Conclusions: Future research on regional fire patterns, including fire severity, will enhance opportunities for collaborative efforts between countries, improve knowledge about ecological patterns and processes in the borderlands, and support long-term planning and restoration efforts.

Keywords: burn mapping, fire regimes, Madrean Archipelago, remote sensing, spatial attributes

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Resumen

Antecedentes: Información sobre los regímenes de fuegos contemporáneos que ocurren a través de las cadenas montañosas de Sky Island en la eco-región del archipiélago Madrean en el sudoeste de los EEUU y el norte de México pueden brindar una visión sobre como el manejo histórico del fuego ha influenciado los regímenes de fuego, y puede ser usado como guía para el manejo de combustibles, la restauración ecológica y la conservación del hábitat. Para contribuir a una mejor comprensión de los patrones espaciales y temporales de fuegos en la región relacionados con influencias ambientales y antrópicas, aumentamos el perímetro de datos existente para los EEUU mediante el mapeo de incendios que ocurrieron en las cadenas montañosas de Sky Islands en México desde 1985 hasta 2011.

Resultados: Un total de 254 incendios fueron identificados a través de toda la región: 99 incendios en México ($\mu = 3901$ ha, $\sigma = 5066$ ha) y 155 en los EEUU ($\mu = 3808$ ha, $\sigma = 8368$ ha). Los sitios denominados las Animas, Chiricahua, Huachuca-Patagonia, y las montañas de Santa Catalina en los EEUU, y El Pinito en México concentraron la mayor proporción del área quemada (>50%) en relación al tamaño de la región Sky Island. Las Sky Islands adyacentes al límite entre los dos países tuvieron el mayor número de incendios, y muchos de ellos fueron grandes y con formas complejas. Los incendios ocurrieron más frecuentemente en biomas remotos, caracterizados por bosques siempreverdes y bosques de coníferas con condiciones frías y húmedas. Los incendios más grandes (>25 000 ha) ocurrieron durante las primeras sequías del siglo XXI (2002 a 2003, y 2011); cuatro de ellos fueron en los EEUU y uno en México. En general, una gran variación en forma y tamaño de incendios fue observado entre años húmedos y secos, contribuyendo a la heterogeneidad del paisaje a través de la región.

Conclusiones: Investigaciones futuras en el patrón regional del fuego, incluyendo la severidad, va a mejorar las oportunidades para los esfuerzos colaborativos entre ambos países, mejorar el conocimiento sobre los patrones y procesos ecológicos en áreas fronterizas, y apoyar planificaciones a largo plazo y esfuerzos en la restauración.

Abbreviations

ATCOR: ATmospheric CORrection
dNBR: differenced Normalized Burn Ratio
FIRMS: Fire Information for Resource Management System
GLOVIS: GLOBAL VISualization Viewer
MODIS: MODerate resolution Imaging Spectroradiometer
MTBS: Monitoring Trends in Burn Severity
NBR: Normalized Burn Ratio
NIR: Near InfraRed
PSDI: Palmer Drought Severity Index
scPSDI: self-calibrating Palmer Drought Severity Index
SEDAC: SocioEconomic Data and Applications Center
SRTM: Shuttle Radar Topography Mission
SWIR: ShortWave InfraRed
USAID: US Agency for International Development
USGS: United States Geological Survey

Background

In today's world, understanding between neighboring countries is more vital than ever (Riding 1989). Although the importance of history, culture, and socioeconomic conditions is often emphasized, ecological processes that shape the distribution of species and communities, and thus support resources essential to human livelihoods, are equally critical components of integrated systems that transcend political borders (Liu et al. 2007). Wildland fire is an important ecological process that shapes the distribution of species and

communities and associated ecosystem services. Wild-fire can enhance or reduce species habitat and connectivity, alter water cycle processes and induce erosion, and influence forest carbon budgets (Cannon et al. 2010, Hurteau and Brooks 2011, Williams et al. 2014, Hutto et al. 2016). Information on the timing, location, and patterns of fires is key to understanding the physical, biological, and ecological processes that generate those patterns, including evolutionary processes that drive biological and ecological diversity upon which people depend (Bond and Keeley 2005, Burton et al. 2009, Whitman et al. 2015).

Maps of fire occurrence are a key resource in management and ecological restoration efforts, and can provide insight into the effects of land use, climate, and topography on contemporary fire regimes (Morgan et al. 2001; Stephens and Fulé 2005; Miller et al. 2012a, b). Where available, consistent and accurate data on fire regimes, including frequency, severity, and spatial pattern, facilitate important decisions regarding sustainable forest management and reduction of fuels to control fire risk (Bergeron et al. 2004, Petrakis et al. 2018). Furthermore, fires increase the spatial heterogeneity of vegetation at multiple scales; knowledge of fire regime attributes can be used to understand how fires create, maintain, or otherwise alter wildlife and plant habitats, as well as how fires support or disrupt the connectivity of those habitats (Zozaya et al. 2011). Importantly, fire regimes are

expected to change with climate; alterations have already been observed at local to global scales (Hurteau *et al.* 2014). In places where resources necessary to develop and support fire mapping programs are limited, it is impossible to address these priority issues in a way that is comparable with adjoining countries in which mapping programs are well established.

In the US, federal agencies developed the Monitoring Trends in Burn Severity (MTBS) program to provide a comprehensive, national database of wildfire information about “large” fires (>404 ha in the West and >202 ha in the East) from 1984 to the present (Eidenshink *et al.* 2007). MTBS data have been used to examine regional and national wildfire trends related to vegetation type, topography, forest management, and climate, providing information to guide policy and management decisions (Wimberly *et al.* 2009, Dillon *et al.* 2011, Miller *et al.* 2012a, Baker 2013). Prior to our efforts, a fire database for northern Mexico that is comparable to MTBS did not exist, and institutional information on wildfires that burned in remote areas was lacking due primarily to complex land ownership (*i.e.*, more communal and private land in forests of Mexico compared to lands administered by federal agencies in the US) and limited forestry and firefighting budgets (Rodríguez-Trejo 2008, Villarreal and Yool 2008). Our work is an important first step in characterizing contemporary fire regimes in a cross-border region with outstanding biodiversity (Whittaker and Nearing 1965, Coblentz and Riitters 2004) that is expected to experience the ecological impacts of climate change sooner than other areas of western North America (Notaro *et al.* 2012).

The objectives of this research were to quantify the spatial and temporal patterns of recent (1985 to 2011) fire occurrence across the Madrean Archipelago Ecoregion of North America, and to analyze these patterns relative to significant climate, topography, ignition sources, and land cover variables. The Madrean Ecoregion provides a unique setting to study spatial patterns of wildfire: mountains in the ecoregion are biogeographically similar, but the region is divided in half by the United States–Mexico international border, where contrasting land uses and forest management approaches often occur. We posed the following questions:

- 1) What are the basic characteristics of contemporary fire regimes across the study region?
- 2) How do spatial patterns of fires vary regionally, and within each Sky Island mountain range?
- 3) How does inter-annual climate variability influence fire patterns?
- 4) How does underlying spatial heterogeneity in climate, topography, ignition sources, and land cover define burned and unburned environments?

Methods

Study area

Covering a geographic area of approximately 74 788 km², the Madrean Archipelago Ecoregion (Omernik 1987) encompasses portions of northern Sonora and Chihuahua in Mexico, and southeastern Arizona and southwestern New Mexico in the US (Fig. 1). Characterized by a basin and range topography with elevations ranging from 600 m in the valley floors (Tepache, Sonora) to 3267 m (Mount Graham, Arizona), the Madrean Archipelago consists of isolated forested mountains (referred to as Sky Islands) surrounded by desert lowlands, semi-arid grasslands, and shrub steppe vegetation (Warshall 1995). The ecoregion contains 39 Sky Island mountain complexes that make up more than half of the total land area (42 729 km²; Fig. 1; Warshall 1995). The international border, established after the Gadsden Purchase in 1853, cuts through the center of the ecoregion at 31°33' N (Fig. 1). Twenty-two of the Sky Islands fall primarily within the US and 17 in Mexico. Three ranges—the Atascosa-Cibola, Huachuca-Patagonia, and Peloncillo-Pan Duro—cross the international border. Characteristics of the 30 Sky Islands that had fires during the study period are presented in Table 1.

Climate of the Madrean Archipelago is characterized by a bimodal precipitation pattern. Winter (November to March) frontal storms bring snow to higher elevations and rain to the lower elevations. In mid to late summer (July to August), moisture from the south creates a monsoonal weather pattern with thunderstorms. The arid foreshummer period (April to June) preceding the monsoonal moisture is typically hot and dry and generally corresponds to the fire season. Annual precipitation varies greatly by elevation, with orographic uplift contributing to increased precipitation at upper elevations. The average annual precipitation ranges from about 232 mm at 820 m above sea level to 1035 mm at 3267 m (Fort Thomas, Arizona, and Mount Graham, Pinaleno Mountains, respectively; Hamann *et al.* 2013).

Sky Island Vegetation

Upland vegetation of the ecoregion generally consists of Sonoran Desertscrub, Chihuahuan Desertscrub, and Sinaloan Desertscrub, and Semidesert Grasslands in the low-elevation valleys and flats, and Madrean Evergreen Woodlands, Montane Conifer Forests, and Subalpine Conifer Forests at the upper elevations (Brown *et al.* 1979). The sharp vertical relief and unique geographic position of the Sky Islands combine to create a diverse mosaic of vegetation assemblages stratified along elevation and moisture gradients (Niering and Lowe 1984). The Rocky Mountain Cordillera vegetation influence from the north is more prevalent at higher elevations (above 2000 m) while the Madrean vegetation influence from the south dominates

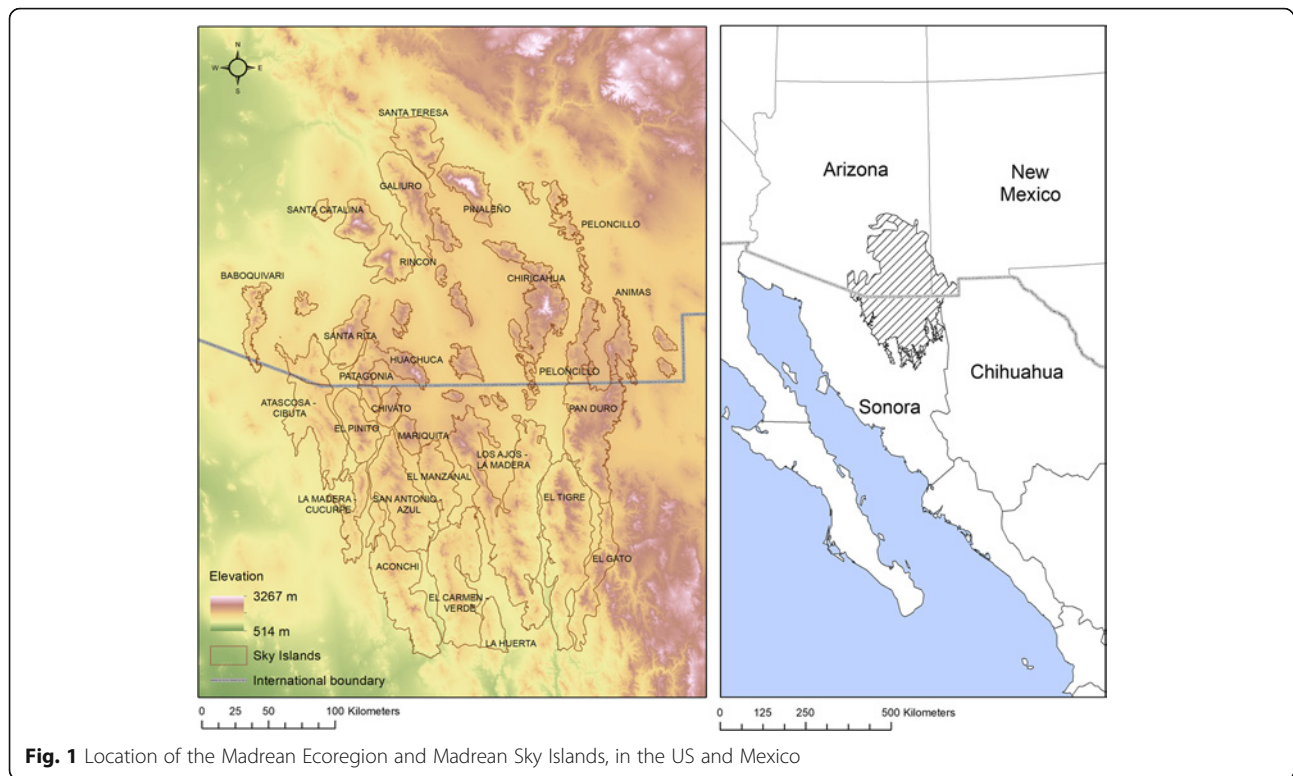


Fig. 1 Location of the Madrean Ecoregion and Madrean Sky Islands, in the US and Mexico

lower elevations (below 2000 m) (McLaughlin 1994). Coniferous vegetation within the Sky Islands is generally divided into five types: pinyon–juniper woodlands, Madrean evergreen woodlands, pine–oak forests, pure pine forests, and mixed-conifer forests (Iniguez et al. 2005).

Pinyon–juniper woodlands typically occur in areas below 1800 m elevation, although they can also be found at higher elevations on drier south-facing aspects. The dominant tree species within the pinyon–juniper plant community include alligator juniper (*Juniperus deppeana* Steud.), Rocky Mountain juniper (*J. scopulorum* Sarg.), one-seed juniper (*J. monosperma* [Engelm.] Sarg.), pinyon pine (*Pinus edulis* Engelm.), and border pinyon (*P. discolor* D.K. Bailey and Hawksw). Madrean oak woodlands generally occur at low to mid elevation and are dominated by evergreen oak including silverleaf oak (*Quercus hypoleucoides* A. Camus), Arizona white oak (*Q. arizonica* Sarg.), Emory oak (*Q. emoryi* Torr.), and Mexican blue oak (*Q. oblongifolia*). Mid-elevation pine forests are dominated by ponderosa pine (*P. ponderosa* C. Lawson) and Gambel oak (*Q. gambelii* Nutt.). Higher elevation forests are dominated by Apache pine (*P. engelmannii* Carr.), Chihuahua pine (*P. leiophylla* Schiede & Deppe), and Arizona pine (*P. arizonica* Engelm.). Mixed-conifer forests are generally found between 2500 and 3000 m and typically include Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Fanco), white fir (*Abies concolor* [Gord. & Glend.] Hildebr.), southwestern white pine (*P.*

strobiformis Engelm.), quaking aspen (*Populus tremuloides* Michx.), and ponderosa pine.

Cultural history

The oldest known inhabitants of the general area were the Hohokam, who, as farmers, mainly occupied the desert valley bottoms near reliable water sources (Waters and Ravesloot 2001). Apaches moved into southwestern Arizona in the 1680s and 1690s and, unlike prior inhabitants of the Southwest, they utilized both valley bottoms and upland forests (Bahre 1991). Spanish settlers began moving into the region in the sixteenth and seventeenth centuries, and by the 1600s, they had established settlements around missions near major rivers including the San Pedro, Santa Cruz, Magdalena, and the Rio Sonora (Clemensen 1987). Demand for timber for construction and fuel in the new settlements had a considerable impact on the surrounding forests (Bahre and Hutchinson 1985). However, the presence of Apache groups restricted Euro-American settlement in and around high-elevation forests of the Sky Islands until the end of the nineteenth century (Bigelow Jr 1968).

After the Gadsden Purchase in 1853, the region was divided and the current political borders were established; around this time, the arrival of the Southern Pacific Railroad and subjugation of the Apaches led to an increase in Euro-American settlement that brought about significant land use changes (Bahre 1991). Between 1902 and 1907,

Table 1 Madrean Ecoregion Sky Islands, US and Mexico, size and elevation characteristics, sorted by country then area (km²). Elevation values were derived from Shuttle Radar Topography Mission (STRM) 30 meter Digital Elevation Model (Farr et al. 2007). Mapped locations of each Sky Island can be found in Fig. 1

Sky Island	Country	Area (km ²)	Perimeter (km)	Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)	Median elevation (m)
Chiricahua	USA	1802	522	1202	2988	1802	1751
Galiuro	USA	1663	247	726	2321	1390	1359
Huachuca-Patagonia	USA	1194	292	1141	2878	1636	1605
Santa Teresa	USA	1060	173	839	2483	1396	1356
Rincon	USA	971	194	834	2641	1372	1295
Pinaleno	USA	920	189	998	3267	1767	1656
Santa Rita	USA	895	174	1018	2855	1473	1425
Santa Catalina	USA	853	138	778	2792	1498	1422
Peloncillo	USA	685	616	1014	1978	1406	1400
Baboquivari	USA	609	357	860	2255	1267	1235
Animas	USA	599	316	1404	2603	1720	1695
Mule	USA	369	170	1324	2241	1641	1610
Whetstone	USA	232	131	1306	2339	1662	1621
Perilla	USA	212	252	1185	1923	1447	1428
Big Hatchet	USA	169	66	1315	2540	1620	1585
Sierrita	USA	164	102	793	1886	1360	1322
Swisshelm	USA	147	69	1359	2184	1591	1570
Los Ajos-La Madera	Mexico	5588	935	542	2621	1308	1304
El Tigre	Mexico	3591	437	417	2447	1266	1243
Peloncillo-Pan Duro	Mexico	3523	788	894	2522	1638	1644
El Carmen-Verde	Mexico	2955	412	499	1996	1098	1081
Atascosa-Cibuta	Mexico	2689	527	745	2073	1206	1206
Aconchi	Mexico	2477	331	441	2185	1024	996
San Antonio-Azul	Mexico	2355	298	778	2452	1339	1318
El Gato	Mexico	1361	304	669	2428	1408	1378
El Pinito	Mexico	1038	171	889	2220	1378	1338
La Madera-Cucurpe	Mexico	883	318	781	2042	1160	1126
La Huerta	Mexico	573	122	485	1784	893	873
Mariquita-Elenita	Mexico	368	83	1267	2495	1628	1577

several federal forest reserves were established in the Sky Islands of Arizona and New Mexico (Allen 1989). Following the historic fires of 1910 in the western US, federal land management agencies adopted aggressive fire suppression policies (Pyne 1982). In 1935, the US Forest Service established the “10 a.m. policy,” with the goal of suppressing every fire by 10 a.m. the day following its initial report. Fire suppression became even more effective after the Second World War with advancement in fire-fighting technologies, particularly more abundant aircraft and fire suppressing chemicals.

In northern Mexico, many of the Sky Island forests were part of privately owned *haciendas* until the

Mexican Revolution (1910 to 1920) and the passing of the Agrarian Code in 1934, which reallocated private lands to local communities, called “*ejidos*” (Thoms and Betters 1998). Unlike in the United States where much of the forest land was federally managed, under the *ejido* system, local communities were responsible for managing forests and wildfires; therefore, wildfires in northern Mexico were not suppressed to the same extent that they were in the western US. During the 1980s, the forest service of Mexico, aided by the US Forest Service and US Agency for International Development (USAID), developed a more active fire management program (Rodriguez-Trejo et al. 2011); however, the scale of

firefighting in Mexico during that period was much smaller, with Mexico spending around one tenth of the dollar amount per acre on wildland firefighting activities compared to the US (Villarreal and Yool 2008).

Fire history

Prior to the twentieth century, wildfires within the Madrean Sky Islands were relatively common, particularly at higher elevations where greater productivity created abundant fuels and a dry pre-monsoon period allowed these fuels to cure and then burn (Baisan and Swetnam 1990). Tree-ring based fire history studies have found that, prior to the 1900s, pine-dominated sites experienced, on average, large fires every 6 to 15 years (Swetnam et al. 2001, Meunier et al. 2014). Mixed-conifer sites, on the other hand, experienced large fires less frequently at intervals ranging from 8 to 25 years (Swetnam and Baisan 1996, Iniguez et al. 2008, Margolis et al. 2011). While fire severity varied by site, fires in places historically dominated by pines were predominantly low severity (Swetnam et al. 2001, Iniguez et al. 2009).

Reduced wildfire activity in the mountains surrounding major human settlements has been documented for the US Sky Islands at the end of the nineteenth century (Baisan and Swetnam 1990, Swetnam et al. 2001). These changes have been associated with a sequence of historical events: the end of the Apache wars, the arrival of the railroad, and the introduction of large-scale livestock grazing. As a result, fine fuels required for fire spread were effectively removed over large areas (Savage and Swetnam 1990, Belsky and Blumenthal 1997).

North of the border, the last large wildfires prior to fire suppression occurred between 1900 and 1910; to the south, this process was delayed until the 1930s, following the Mexican Revolution (1910 to 1920). While some authors suggest that the allocation of *ejidos* marks the onset of fire suppression (Heyerdahl and Alvarado 2003), this is not the case for some sites in the Madrean Archipelago or even farther south (Kaib 1998, Cortés Montaña et al. 2012). However, in Mexico, the exclusion of wildfire was less extensive; in some more remote locations, frequent fires continued up to the present day (Fulé et al. 2011, Meunier et al. 2014). Moreover, some of these sites where fires still persist contain forest conditions similar to those believed to dominate the region prior to fire suppression (Cortés Montaña et al. 2012, Yocum Kent et al. 2017).

Fire identification with satellite imagery

Since information on dates and locations of many past fires was not available for the Sky Islands in Mexico, we used a semi-automated remote sensing fire-mapping approach to identify and delineate fires that occurred within the Mexican Sky Island mountain ranges. Our

approach adapted satellite-based fire mapping and burn severity techniques used by MTBS in the US that are typically applied on an *ad hoc* basis, with knowledge of specific fire date and location (Monitoring Trends in Burn Severity: <https://mtbs.gov/mapping-methods>). The techniques take advantage of the changes in spectral information observed in remotely sensed imagery.

Post-fire mapping of burned area and severity are typically accomplished either through visual interpretation of aerial photography, or by using band-ratio techniques on satellite spectral information (White et al. 1996, Miller and Yool 2002, Lentile et al. 2006). Landsat multispectral imagery has proven suitable for fire mapping, as the data are relatively high resolution (30 m) with a 16-day return, and contain shortwave infrared (SWIR) and near infrared (NIR) information that can be used to discriminate a range of burn severity classes (White et al. 1996). The MTBS method uses Landsat data to identify fire perimeters and estimate burn severity classes using the differenced Normalized Burn Ratio (dNBR) method (Eidenshink et al. 2007). The Normalized Burn Ratio (NBR) is derived from the near infrared reflectance in Landsat band 4 (0.63 to 0.69 μm) and shortwave infrared reflectance in band 7 (2.08 to 2.35 μm) from a single Landsat image (Cocke et al. 2005, Key 2006), and the dNBR is a simple differencing of pre- and post-fire NBRs. The NBR equation is as follows:

$$\text{NBR} = \frac{(\text{Band 4} - \text{Band 7})}{(\text{Band 4} + \text{Band 7})} \quad (1)$$

An important aspect of the dNBR is careful selection of pre- and post-fire images to reduce error introduced by changes in scene conditions, including vegetation phenology and climate-induced conditions (Key 2006). Land surface and atmospheric conditions such as snow, vegetation change in wet versus dry seasons, shadows, smoke, and clouds all affect the outcome of the dNBR product (Key 2006).

The two steps of our semi-automated process were as follows: the first step involved calculating the NBR for a spring or early summer (assumed to be pre-fire) and a fall or early winter (assumed to be post-fire) Landsat scene of each year (1985 to 2011), calculating a dNBR with the two NBRs, then applying a dNBR threshold to identify locations where vegetation change was likely due to fire and to eliminate many non-fire related pixel changes (Prickett 2013). To calculate the dNBRs, we obtained 1517 cloud free Landsat 5 TM images (1985 to 2011) from the USGS Global Visualization Viewer (GLOVIS) website for seven Landsat path or row designations that cover the Madrean Archipelago Ecoregion. All images were corrected for atmospheric effects and haze, and converted to reflectance using the ATmospheric CORrection (ATCOR)

module for ERDAS Imagine. The dNBR-derived detections were then filtered by size (<100 ha) and location (intersecting Sky Island polygons) to remove small non-fire vegetation changes (e.g., changes from productive agricultural fields to fallow), and positive identifications were converted to polygons. An initial accuracy assessment of fire detections tested against MODIS Fire Information for Resource Management System (FIRMS) daily detections (from 2001 to 2011) indicated that the automated process correctly identified about 42% of the fires in Mexico during this period.

The second step involved manually identifying additional fires in Mexico through visual interpretation using a combination of dNBR images and false color composites (displaying bands 6, 4, and 3 in RGB) from the full Landsat archive. Once identified, fire perimeters were digitized on screen using the dNBR and post-fire color composites. To assess omission errors that may have occurred due to data limitations (e.g., too many cloudy scenes during post-fire period to detect fire scar), we validated the burn perimeter data with MODIS FIRMS daily detections from 2001 to 2011. We also validated MTBS fires in the US with the FIRMS dataset to identify any

commission errors in that dataset and to better ensure comparability of fire regimes across the region from different data sources and methods.

Derived and ancillary datasets

Using the fire perimeter polygons (rasterized using 100 m [1 ha] cell size), we developed a database of patch statistics for each fire, including those that overlap (Table 2). We selected a set of metrics that were representative of several attributes including size, shape, and orientation. The metrics allow characterization of fire patterns that may reflect underlying aspects of the environment or important ecological processes (Table 2).

To represent regional climate conditions through the study time period, we obtained the self-calibrating Palmer Drought Severity Index (scPDSI; van der Schrier *et al.* 2013). The scPDSI provides a standardized, time-integrated drought index that takes into account precipitation, temperature, and available moisture capacity of soils (van der Schrier *et al.* 2013). A variation of the original Palmer Drought Severity Index (Palmer 1965, Osborn *et al.* 2017), scPDSI was developed to provide more robust comparisons across

Table 2 We quantified fire spatial patterns using metrics representing fire size, shape, and orientation. The table includes a reference for the program used to calculate the metrics, a general description of each, and a summary of their potential ecological significance in terms of pattern–process relationships of interest. Madrean Ecoregion Sky Islands, US and Mexico, 1985 to 2011

Spatial pattern attribute	Spatial pattern metric (R package used for computation)	General description	Ecological significance
Size	Fire size (VanDerWal <i>et al.</i> 2014)	Area of each fire (ha)	The distribution of fires of varying size defines an important component of a fire regime. Fire size can be influenced by climate (Haire and McGarigal 2009), as well as underlying features of topography that either facilitate or impede fire spread (Mansuy <i>et al.</i> 2014). Greater interior, or core area, reflects a higher proportion of area burned that is isolated from the surrounding unburned matrix and its intact resources. Interior areas are likely to experience very different physical conditions than disturbed areas near intact vegetation (Turner <i>et al.</i> 2001).
	Core area index (VanDerWal <i>et al.</i> 2014)	The interior area of the fire, greater than 100 m from the fire perimeter as a percentage of patch area	
Shape	Eccentricity (Bui <i>et al.</i> 2012)	Ratio of the distance between the two farthest extremities of each fire and the distance of the maximum width of its perpendicular axis (<i>i.e.</i> , length-to-breadth)	Fire shape can reflect underlying factors such as physiography, hydrography, and surficial deposits (Mansuy <i>et al.</i> 2014), time period, vegetation, climate, and management (Parisien <i>et al.</i> 2006). Shape interacts with fire size and severity to influence rate and direction of successional trajectories (Turner <i>et al.</i> 1998). Complex fire shapes can include more edge habitats with greater potential interspersions of seed sources.
	Shape index (VanDerWal <i>et al.</i> 2014)	Fire shape complexity; the degree of departure from a circular shape; ranges from 1 (round) to >1 (complex)	
	Perimeter area ratio (VanDerWal <i>et al.</i> 2014)	Ratio of patch perimeter (m) to area (m ²)	
Orientation	Bearing (Hijmans 2016)	Orientation (degrees) of the axis of the two farthest extremities of each fire	The orientation of a burn can reflect predominant winds and/or topographic (e.g., watershed) orientation (Barros <i>et al.</i> 2013). Given this potential interaction with topography, bearing may also influence the traversability of the burned area by wildlife and plants.

diverse climates (van der Schrier *et al.* 2013). Approximately 80% of Sky Island fires occurred between the end of April and the beginning of August (Julian dates 117 to 221), so we selected April to represent pre-fire season conditions. At each fire polygon centroid, we extracted the April scPDSI value for the year that the fire burned. We adopted a standard classification of the index to interpret the results (for drought: extreme < -4 ; severe < -3 ; moderate < -2); wetter classes are assigned the same threshold values, but with positive sign (Palmer 1965, Osborn *et al.* 2017).

In addition, we used several datasets to represent spatial heterogeneity of environmental conditions, including those representing physical and biological factors that influence the occurrence of fire, as well as human presence and activities that affect ignition sources and use and management of fire (Table 3). We obtained a 30 m Shuttle Radar Topography Mission (SRTM; Farr *et al.* 2007) digital elevation model from Google Earth Engine (Gorelick *et al.* 2017) and resampled the data to 1 km resolution for computation of terrain ruggedness. The spatial climate data included 26 bioclim layers developed by the ClimateWNA project (Hamann *et al.* 2013) and were based on 1981 to 2010 climate normals (Table 3). Ignition source data were obtained from National Aeronautics and Space Administration (NASA) (lightning; Albrecht *et al.* 2016); anthropogenic biomes (Ellis and Ramkuttty 2008) and roads were downloaded from Commission for Environmental Cooperation (see CEC 2009). Population density data were obtained from Socioeconomic Data and Applications Center (SEDAC; <http://sedac.ciesin.columbia.edu/>). The lightning, roads, and population density data were smoothed by applying a uniformly weighted kernel (55 km radius window) before sampling. We used Brown and Lowe's Biotic Communities of the Southwest (CBI 2004; available at <http://databasin.org>) to characterize variability in vegetation composition and structure (Brown *et al.* 1979).

Analysis

Characteristics of fire regimes

We used the fire perimeter database to characterize the regional and temporal distribution of fire frequency and area burned for each island and for each year during the study period. We mapped the variability in the landscape structure of fire patterns, including composition (area burned or fire size) and configuration (shape metrics) for each fire across the ecoregion.

Influence of climate on fire patterns

To understand how regional climate influences fire patterns, we used the R package (R Core Team 2017) *ggplot2* (Wickham 2009) to generate a hexagon heatmap of two-dimensional bin counts (pattern metric by year) and graphed the results using a color

gradient of scPDSI values. We specified 20 bins in horizontal and vertical dimensions for the plots. The position of each bin represents the center of mass (average of x , y values) for that bin and the mean scPDSI for the x , y values in each bin determines its color. The hexagon plots provided a visual tool to examine how fire size and shape varied in relation to wetter and drier years and whether patterns across years indicated trends during the study period.

Variation in fire patterns in relation to underlying spatial heterogeneity

We randomly sampled the study region within islands that experienced fire to obtain values for all spatial variables (Table 3). We applied a mask of fire perimeters to sample within areas that burned (total $n = 6670$; US $n = 3699$; Mexico $n = 2971$) and areas that did not burn (total $n = 29\,731$; US $n = 8759$; Mexico $n = 20\,972$). We used the sample data to conduct a graphical analysis of burned and unburned environments.

For categorical variables (anthropogenic biomes and biotic communities; see Table 3), we examined patterns in the data using stacked bar charts, for which height of the bar in each color represents its relative occurrence in burned and unburned samples. For continuous variables, we displayed the distribution of burned samples and unburned samples using smoothed density plots to aid in identifying the environmental space occupied by fires in the US and Mexico. We tested the null hypothesis that samples of burned and unburned environments came from a common population using Anderson-Darling statistics (AD.T; k -sample criterion AD; Scholz and Zhu 2016). Because several of the climate variables exhibited similar patterns, we included five of the 26 climate variables in the results, as well as population density, road density, terrain ruggedness, and lightning flash rate (Table 3).

Results

Validation of fire detections in US and Mexico

A total of 254 fires (>404 ha) were identified across the region from 1985 to 2011, 99 fires in Mexico and 155 in the US. (The fire perimeter database is available from US Geological Survey, see Villarreal and Poitras 2018). Of the 254 fires mapped, 142 occurred between 2001 and 2011 and were validated using MODIS FIRMS detections. All 142 fires were confirmed with FIRMS data (no false positives); however, the FIRMS data set contained six fires that were not mapped by MTBS or captured with our mapping approach for Mexico. Four of the missed fires were located in the US and two in Mexico. In all cases, the fires were not mapped because multiple consecutive

Table 3 Spatial data used to describe fire environments, including topographic, climatic, ignition sources (including human influence), and vegetation in the Madrean Ecoregion Sky Islands, US and Mexico. The spatial density of roads, lightning, and population was calculated using a uniformly weighted kernel (~55 km radius moving window) for use in analysis. The bioclim variables graphed in figures are listed in bold. For biotic communities and anthropogenic biomes, only categories present in the study region are given in the table

Variable	Description
Topography	
Terrain	Terrain ruggedness index derived using a digital elevation model (1 km resolution). Defined as the mean of the absolute differences between the value of a cell and the value of its eight surrounding cells.
Climate	
Spatial climate	ClimateWNA bioclim layers based on climate normals 1981 to 2010 at 1 km resolution (Wang <i>et al.</i> 2016; https://adaptwest.databasin.org/pages/adaptwest-climatena). Bioclimatic variables: MAT: mean annual temperature (°C) MWMT: mean temperature of the warmest month (°C) MCMT: mean temperature of the coldest month (°C) TD: difference between MCMT and MWMT, as a measure of continentality (°C) MAP: mean annual precipitation (mm) MSP: mean summer (May to Sep) precipitation (mm) AHM: annual heat moisture index, calculated as (MAT+10)/(MAP/1000) SHM: summer heat moisture index, calculated as MWMT/(MSP/1000) DD_0: degree-days below 0 °C (chilling degree days) DD5: degree-days above 5 °C (growing degree days) DD_18: degree-days below 18 °C DD18: degree-days above 18 °C NFFD: the number of frost-free days bFFP: the Julian date on which the frost-free period begins eFFP: the Julian date on which the frost-free period ends FFP: frost-free period PAS: precipitation as snow (mm) EMT: extreme minimum temperature over 30 years EXT: extreme maximum temperature over 30 years Eref: Hargreave's reference evaporation CMD: Hargreave's climatic moisture index RH: mean annual relative humidity (%) Tave_wt: winter (Dec to Feb) mean temperature (°C) Tave_sm: summer (Jun to Aug) mean temperature (°C) PPT_wt: winter (Dec to Feb) precipitation (mm) PPT_sm: summer (Jun to Aug) precipitation (mm)
Ignition sources	
Lightning	Average annual density of lightning strikes per unit area (~10.5 km resolution), for 1995 to 2005 (strikes per km ² per year) from NASA Global Hydrology and Climate Center: annual high-resolution data on lightning (Albrecht <i>et al.</i> 2016; https://doi.org/10.5067/LIS/LIS/DATA301).
Roads	Major roads mapped at 1:10 000 000 (CEC 2009, http://www.cec.org/tools-and-resources/map-files/major-roads-2009) and resampled to 1 km resolution.
Human population	United Nations-adjusted population density Gridded Population of the World-v4 output at 30 arc seconds. (Socioeconomic Data and Applications Center: http://sedac.ciesin.columbia.edu/data/collection/gpw-v4), resampled to 1 km resolution.
Human influence	Anthropogenic biomes mapped at 4 km resolution: (CEC 2008, http://www.cec.org/tools-and-resources/map-files/anthropogenic-biomes ; Ellis and Ramankutty 2008). Villages Dense agricultural settlements • Cropped and pastoral: villages with a mix of crops and pasture villages • Pastoral villages: villages dominated by rangeland Croplands Annual crops mixed with other land uses and land covers • Residential irrigated: irrigated cropland with substantial human populations cropland • Residential rainfed mosaic: mix of trees and rainfed cropland with substantial human populations • Populated irrigated cropland: irrigated cropland with minor human populations • Populated rainfed cropland: rainfed cropland with minor human populations Rangeland Livestock grazing; minimal crops and forests • Residential rangelands: rangelands with substantial human populations

Table 3 Spatial data used to describe fire environments, including topographic, climatic, ignition sources (including human influence), and vegetation in the Madrean Ecoregion Sky Islands, US and Mexico. The spatial density of roads, lightning, and population was calculated using a uniformly weighted kernel (~55 km radius moving window) for use in analysis. The bioclim variables graphed in figures are listed in bold. For biotic communities and anthropogenic biomes, only categories present in the study region are given in the table (*Continued*)

Variable	Description
	• Populated rangelands: rangelands with minor human populations • Remote rangelands: rangelands with inconsequential human populations
Forested	
Forests with human populations and agriculture	• Populated forests: forests with minor human populations • Remote forests: forests with inconsequential human populations
Vegetation	
Biotic communities	Brown and Lowe's Biotic Communities of the Southwest (Brown <i>et al.</i> 1979; https://databasin.org/maps/new#datasets=e8e241e869054d7e810894e5e993625e). Source scale 1:1 000 000. Map developed by The Nature Conservancy, Arizona, USA, in 2004.
Conifer Forest/Woodland	• Petran Subalpine Conifer Forest • Great Basin Conifer Woodland • Petran Montane Conifer Forest
Evergreen Woodland	• Madrean Evergreen Woodland • Interior Chaparral
Thornscrub	• Arizona Upland Subdivision - Sonoran Desertscrub • Sinaloa Thornscrub • Chihuahuan Desertscrub • Plains of Sonora Subdivision - Sonoran Desertscrub
Grassland	• Semidesert Grassland • Plains and Great Basin Grassland

post-fire Landsat scenes were obscured by clouds, making it impossible to accurately delineate a burn perimeter before regrowth occurred.

Characteristics of Sky Island fire regimes: number of fires and fire size

Mean fire size for all fires (254) during the period was 3847 ha (σ = 7262 ha), with similar mean fire size in Mexico and the US (3901 ha and 3808 ha, respectively). However, the range and variability in fire sizes differed between countries (Mexico σ = 5066 ha, maximum = 28 519 ha; US σ = 8368 ha, maximum = 91 476 ha). During our period of analysis, there were four distinct large fire years (1989, 1994, 2002, and 2011), each of which included more than 20 large fires and burned more than 75 000 ha yr⁻¹, with a maximum of 231 249 ha burned in 2011 (Fig. 2). Fire patterns during some large fire years varied across the ecoregion; much of the fire activity and area burned in 1994 occurred in the US (Fig. 2) and, in 2011, the area burned in US Sky Islands was more than twice that of Mexico, with the Horseshoe II Fire (91 476 ha) in the Chiricahua Mountains contributing to that difference (Fig. 2). Over the entire study period, the Pan Duro, Huachuca-Patagonia, and Los Ajos-La Madera experienced the greatest number of fires (37, 25, and 21, respectively; Fig. 2). The Pan-Duro had the most hectares burned (136 530 ha), followed by the Chiricahua (116 004 ha) and Atascosa-Cibuta mountains (89 048 ha).

When normalized as a percentage of total Sky Island area, the following Sky Islands had considerable area affected by fire: Animas Mountains (island area = 59 938 ha; total area burned = 84 414 ha), El Pinito (island area = 103 802 ha; total area burned = 69 334 ha), Chiricahua Mountains (island area = 180 217 ha; total area burned = 116 004 ha), Santa Catalina (island area = 85 317 ha; total area burned = 52 490 ha), and Huachuca-Patagonia (island area = 119 386 ha, total area burned = 60 424 ha) (Fig. 2).

Variation in spatial and temporal patterns of fire patch metrics

Maps of fire size and core area index (*i.e.*, interior area of the fire, greater than 100 m from the fire perimeter as a percentage of fire size) indicate that many of largest fires and fires with considerable core area (>0.90) occurred along the border in the Atascosa-Cibuta, El Pinito, and Pan Duro mountains, and in the Chiricahua and Santa Catalina mountains in the US (Fig. 3). Eccentricity (*i.e.*, ratio of the distance between the two farthest extremities of each fire and the distance of the maximum width of its perpendicular axis, or length-to-breadth ratio) was generally high for most fires (*i.e.*, >0.6), indicating more elongated shapes. Shape index (*i.e.*, fire shape complexity; the degree of departure from a circular shape; ranges from 1 [round] to >1 [complex]) varied widely by fire and range, but complexity tended to be

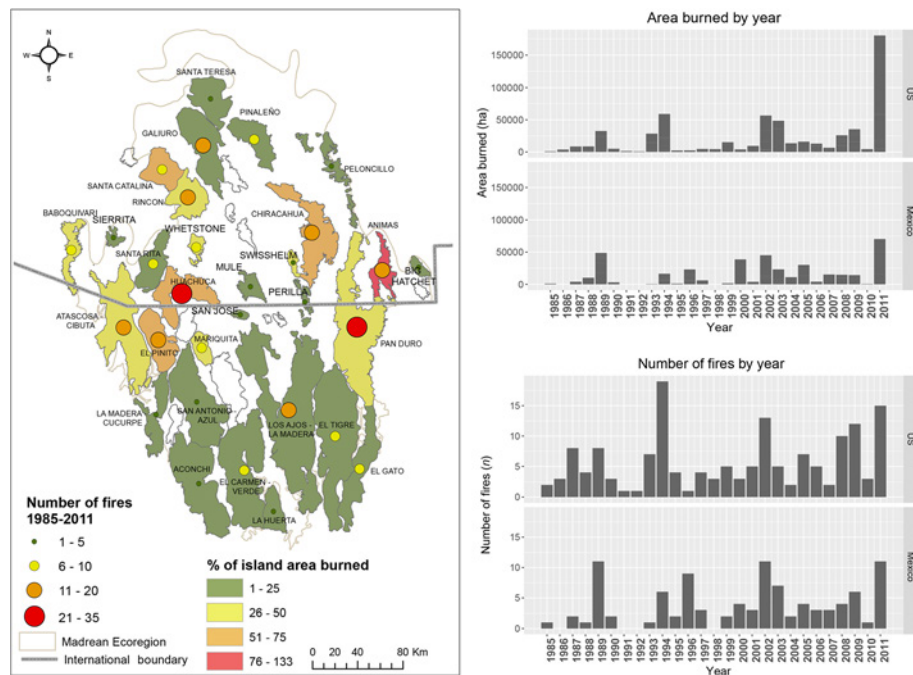


Fig. 2 Number of fires and area burned between 1985 and 2011 for the Madrean Ecoregion, by Sky Island and by country. 1989, 1994, 2002, and 2011 were active fire years. Most of the islands with large amounts of burned area occurred at middle latitudes

higher for fires in Sky Islands on or adjacent to the border, and north of the border.

Influence of regional climate

The scPDSI patterns indicated that drier and wetter pre-fire seasons generally alternated, but multiple, consecutive dry seasons ($\text{scPDSI} < -2$) became more frequent after year 2000 compared to earlier years (Fig. 4). Across years and in relation to climate, spatial patterns were heterogeneous, with a fairly wide range of metric values. Maximum fire size generally increased through time, and this trend was driven by several large fire events that occurred during the droughts of 2000 to 2003 and 2011 (Fig. 4a). Interior areas of fires reflected a lower range of values in early, wetter years (pre-fire season $\text{scPDSI} > 2$) and a clustering of higher values in recent, drier seasons with $\text{scPDSI} < -2$ (*i.e.*, core area index; Fig. 4b). Shapes, overall, varied in complexity, but the upper range of values for Perimeter Area Ratio exhibited a decreasing trend across years with variable climate (Fig. 4c). More circular shapes, (*i.e.*, shape index < 2) were common, but fires with highly complex shapes were less frequent across years and across variability in scPDSI (Fig. 4d). Recent, drier seasons ($\text{scPDSI} < -2$) produced some of the most complex shapes, but 2001, a year with wetter values ($-2 < \text{scPDSI} > 2$),

particularly for some fires, also included complex shapes. Eccentricity, or the length-to-breadth ratio, indicated that many of the fires tended toward elongated, rather than circular, shapes (index value > 0.6 ; Fig. 4e). Bearing ranged from 23 to 73 degrees (north-northeast to east-northeast) for all fires (Fig. 4f); these values indicate the orientation of the two farthest extremities of each fire (Table 2).

Fire patterns and underlying spatial heterogeneity

Biotic communities that experienced fire occurred in different proportions to those in the unburned landscape (Fig. 5, top). A majority of the burned area occurred in Madrean Evergreen Woodlands and Petran Montane Conifer Forests; these communities occurred in greater proportion on burned versus unburned landscapes. Semidesert Grassland occupied a large proportion of unburned area, and a somewhat lesser proportion of burned landscapes. Unburned areas were predominantly Madrean Evergreen Woodlands and Semidesert Grassland with higher proportions of Arizona Upland Subdivision–Sonoran Desertscrub, Chihuahuan Desertscrub, and Sinaloa Thornscrub than burned landscapes.

Burned and unburned landscapes also differed in anthropogenic biome composition (Fig. 5, bottom). The most noted contrast was in the higher proportion

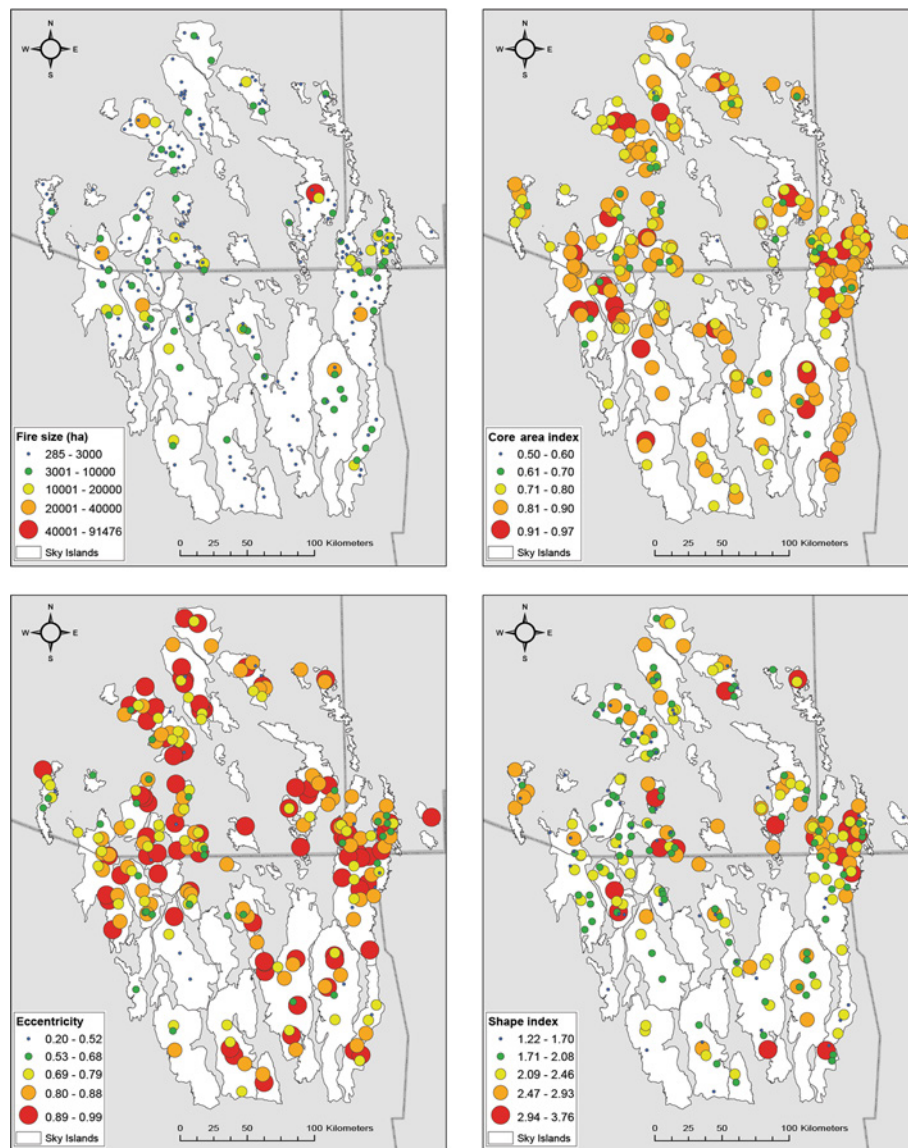
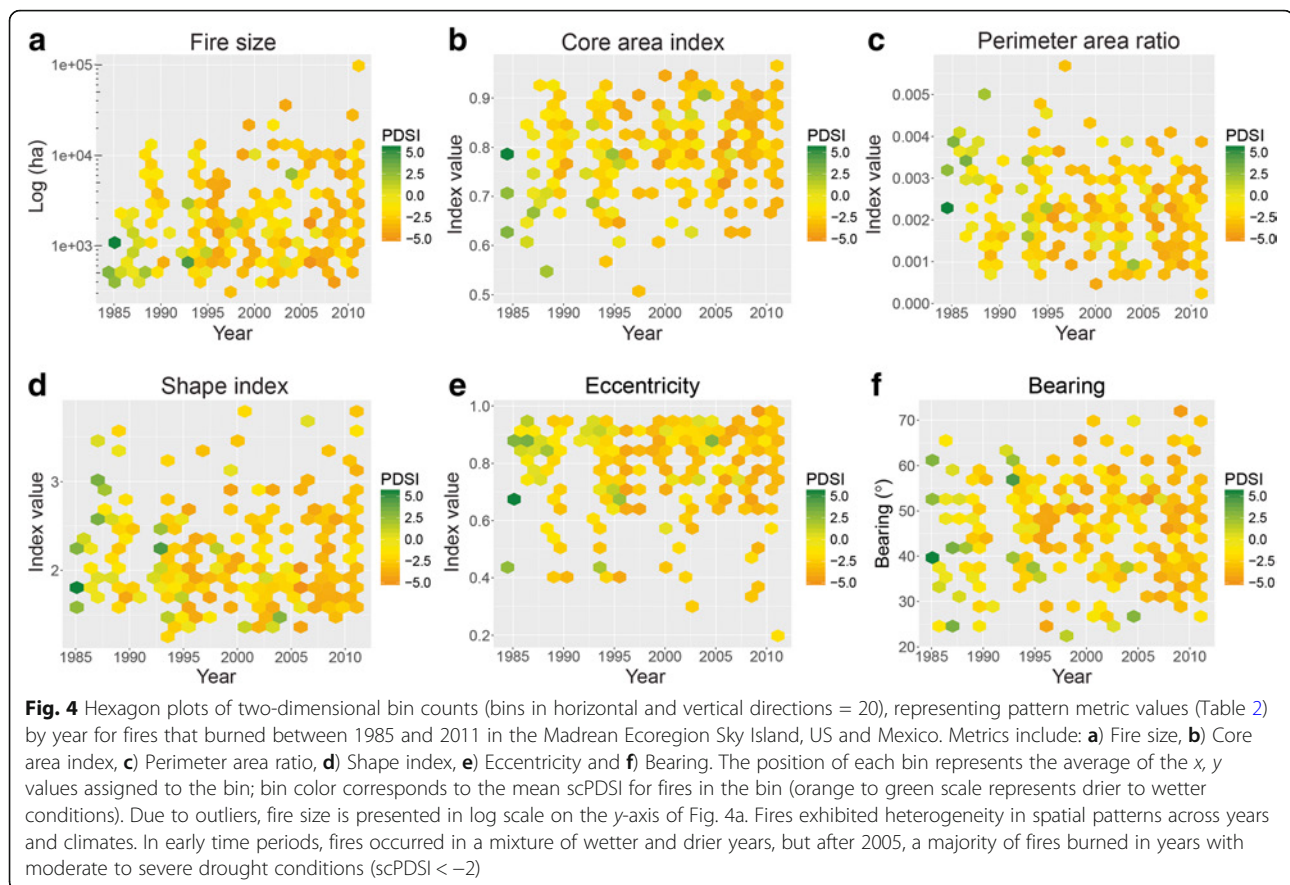


Fig. 3 Distribution of fire patch patterns across the Sky Islands of the Madran Ecoregion, US and Mexico, between 1985 and 2011: fire size and core area index (top row) and eccentricity and shape index (bottom row). Larger fires tended to have greater core area, but more circular (versus more elongated) patterns occurred across the region, as did fires with more or less core area relative to their size

of burned Remote Forests, relative to its abundance in unburned landscapes. Populated Rangelands and Remote Rangelands were less commonly burned than unburned; Villages and Residential anthromes composed a small proportion of the study region, with no evident difference in their occurrence on burned and unburned areas.

Burned areas occupied distinct environments within their unburned context based on visual interpretation of smoothed density plots (Fig. 6) and results of statistical tests (AD.T P -value < 0.001 for all burned-unburned comparisons; see [Appendix](#)).

Results for the climate variables indicated that fire environments occurred at the lower to mid-range of heat moisture in both countries, corresponding to a somewhat higher range of mean annual precipitation and lower range in mean annual temperature (Fig. 6a–c). Fires occurred more often in places with later onset of the frost-free period; this trend was observed in both countries, but the density plot for burned samples was particularly skewed toward later Julian dates for Mexico (Fig. 6d). Burned areas were coincident with a higher range in mean summer precipitation in the US, but the peak in burned sample density occurred at



a slightly lower value for mean summer precipitation (MSP) than the unburned maximum density in Mexico (Fig. 6e).

Natural ignitions did not limit the occurrence of fire, based on the smoothed density plots for US and Mexico (Fig. 6f). Specifically, burned environments were located in the lower range of values for lightning flash rate, as well as in places where rates of lightning strikes were higher. Areas in Mexico with the highest flash rates had lower density of area burned or remained unburned. Population density smoothed plots for burned–unburned samples indicated that fires occurred in very remote areas, as well as more populated areas (Fig. 6g). In Mexico, greater density of unburned samples occurred in sparsely populated areas, compared to burned samples. Burned environments included places with a wide range of road density, especially in the moderate to high range, but in both countries, fires were limited where roads were most prevalent (Fig. 6h). Burned environments were located in flatter, as well as more complex terrain; burned sample distributions tended to encompass places with higher values of terrain ruggedness index for both countries, compared to unburned (Fig. 6i).

Discussion

Characteristics of contemporary fire regimes

Recent fires in the Madrean Ecoregion exhibited several distinctive spatial and temporal patterns. Area burned varied by year and across islands (Fig. 2), but generally increased over the study period, culminating with the 2011 fire year, when the Horseshoe II Fire burned much of the Chiricahua Mountain range in Arizona (91 476 ha), and the El Pinito (28 519 ha) and Murphy Complex fires (26 044 ha) burned along the international border. Fire size in the US was more variable than in Mexico, and much of that variability was related to several large twenty-first century fires. In general, Sky Islands near the border had the greatest number of fires during the period (Pan Duro, 37; Huachuca-Patagonia, 25; and Los Ajos-Madera, 21), and many of the large border fires exhibited complex shapes. As proportion of Sky Island size, the fires in the US tended to burn more area, especially in the Animas, Chiricahua, Huachuca, and Santa Catalina mountains. Many of the southern islands in Mexico had only a few small fires during the study period. The pattern of larger fires north of the international border may be related to observed increases in forest

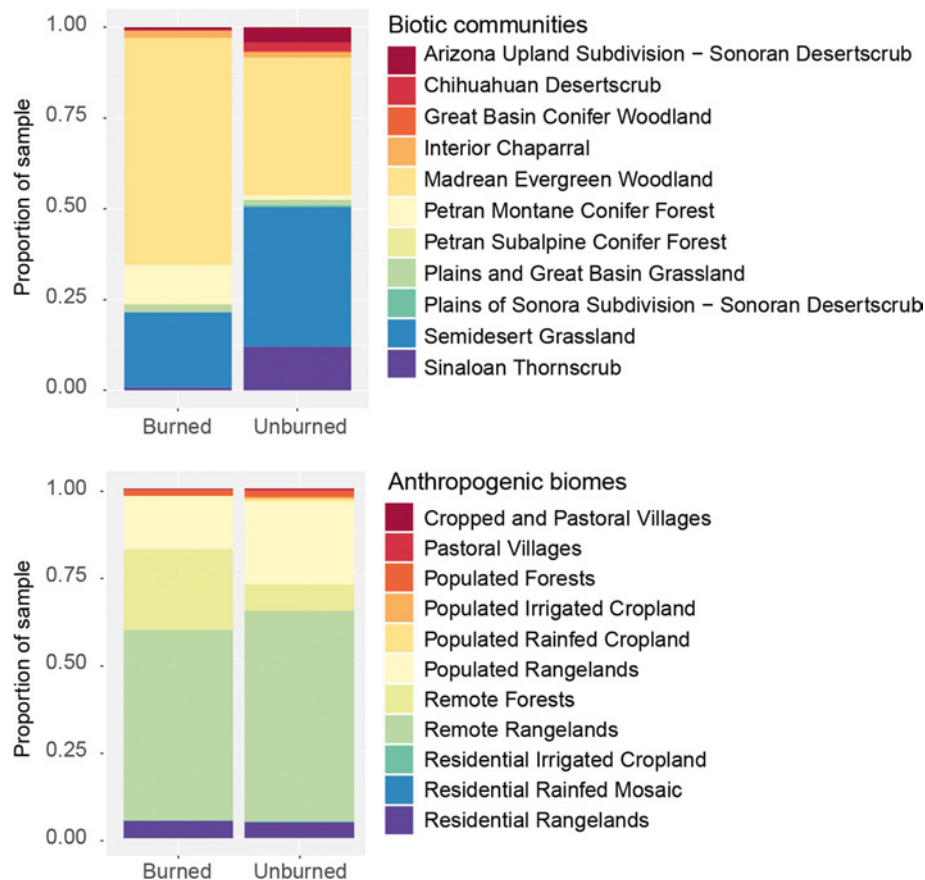


Fig. 5 Differences between burned and unburned areas within biotic communities (top) and anthropogenic biomes (bottom) of the Madrean Ecoregion Sky Islands, US and Mexico, between 1985 and 2011. Comparison of color bar height for each class allows identification of cases where fire occurred disproportionately with regard to biotic and human communities, relative to unburned landscapes

fuel loads at the stand level and related fuel homogeneity at landscape levels due to a longer period of fire exclusion (Moore *et al.* 2004).

Climate and topographic influence on fire patterns

We found that, during our study period, the number of fires and area burned were greatest during drought years identified in other studies (*e.g.*, Dillon *et al.* 2011; Fig. 2). In particular, 1989, 1994, 2002, and 2011 stand out as large fire years, with at least 20 fires (>404 ha) and more than 75 000 ha burned each year. However, we found that fire size and complexity were highly variable in relation to scPDSI, suggesting that fires increased landscape heterogeneity through a range of variation in fire shape and size in years with a mixture of drier and wetter pre-fire seasons (Fig. 4). But we also observed that larger fire sizes followed trends of drought and increased temperature across the region, a trend that is already affecting the distribution of plants in the Sky Islands along an elevational gradient (Brusca *et al.* 2013). The strong relationship between drought and fire was notable for the Sky Islands in the southwestern part

of the ecoregion in Mexico: 12 of the 13 total fires in four Sky Islands (Aconchi, El Carmen-Verde, La Huerta, and La Madera-Cucurpe) occurred during 1989, 1994, 2002, and 2011; however, these fires were generally of moderate size ($\mu = 2911$ ha).

A number of studies in the American Southwest have documented the strong historical relationship between wildfire and antecedent climate (Swetnam and Betancourt 1998, Crimmins and Comrie 2004). Although similar studies that include the Mexican Sky Islands are not as common, a recent study by Meunier *et al.* (2014) in the Sierra San Luis found that, prior to 1886, drought years during the fire year were most conducive for fires. After 1887, in remote areas that continued to burn, the pattern appears to shift and wet conditions the year prior to the fire become a more important factor (Meunier *et al.* 2014). This suggests that wet years result in increased biomass and fuel production that then cures a year later and supports the ignition and spread of fires. Because patterns of scPDSI varied considerably across our study region, the relationship between scPDSI and fires was complex. There is a need to

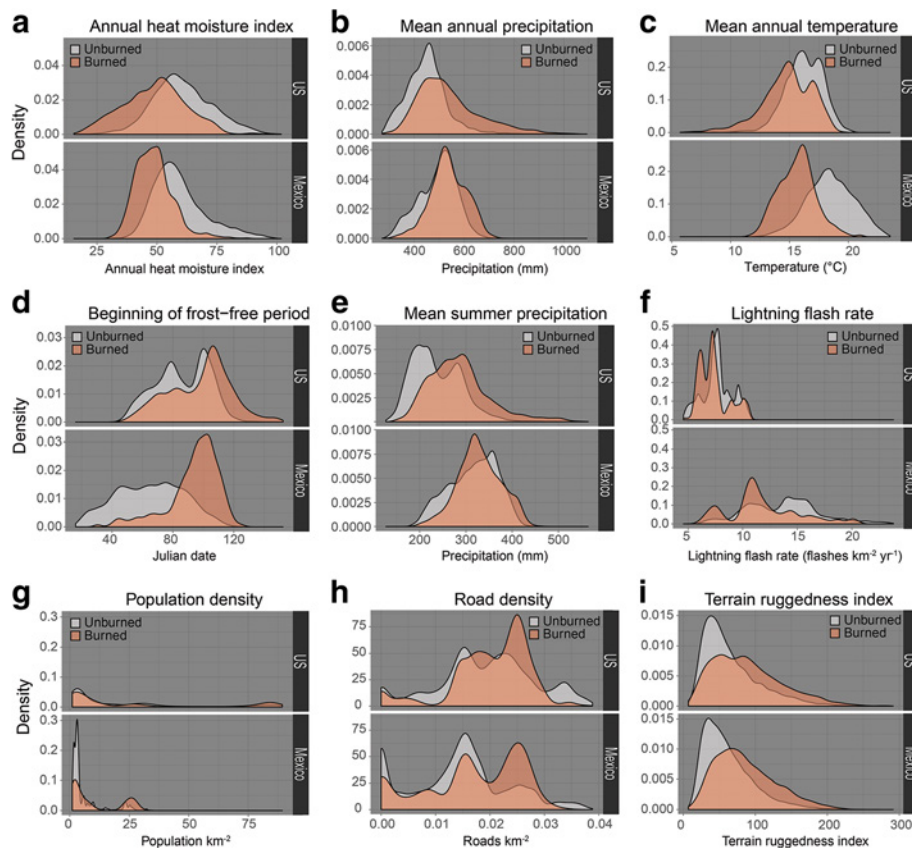


Fig. 6 The smoothed density plots illustrate the distribution of area burned (orange) relative to unburned environments (gray) in the Madrean Ecoregion Sky Islands that experienced fire in the time period of the study (1985 to 2011). Variables considered were: **a**) Annual heat moisture index, **b**) Mean annual precipitation, **c**) Mean annual temperature, **d**) Beginning of frost-free period, **e**) Mean summer precipitation, **f**) Lightning flash rate, **g**) Population density, **h**) Road density, and **i**) Terrain ruggedness index. The top graph for each variable was constructed from random points in US burned–unburned locations; the bottom graph used a set of random points for Mexico. Test comparisons indicated rejection of the null hypothesis that burned–unburned samples came from a common distribution (AD.T P -value < 0.001)

more closely investigate these relationships to better understand how antecedent climate and drought influence the geographic patterns of fire across the Madrean Archipelago region.

Vegetation type and fuel moisture content are driven by elevation and topography that create gradients of temperature, precipitation, and evaporation, thus defining unique fire environments and associated fire regimes (Mansuy et al. 2014, Meunier et al. 2014, Perez-Verdin et al. 2014, Whitman et al. 2015). Our results suggest that many of the fire patterns observed in the Madrean Sky Islands occurred at higher elevations with cooler temperatures, received slightly more precipitation, and had fewer frost-free days than sites that remained unburned (Fig. 6a–d). These areas are dominated by Madrean Evergreen Woodlands and Petran Montane Conifer Forests biotic communities that burned in greater proportion on burned versus unburned landscapes (Fig. 5). Historically, these vegetation types produced enough fuels to support surface fires every 8 to 15 years in these

middle-elevation forests; higher-elevation forests characterized by longer fire intervals occurred in proportions that were comparable to that of unburned landscapes (Fig. 5). The largest fires we observed were on the US side of the border, including the Horseshoe II Fire and the 2003 Aspen Fire in the Santa Catalinas (32 231 ha). These large fires may represent the interactive effects of regional climate and, in some places, a longer history of fire suppression on fuel accumulation and connectivity (Miller et al. 2009).

Human influence on the regional variability of spatial patterns

The importance of understanding the various influences of human activity on fire regimes is increasingly recognized (Mann et al. 2016, Parisien et al. 2016) and takes on a unique relevance in areas where livelihoods are closely dependent on the use of fire (Perez-Verdin et al. 2014). Our geographic analysis revealed patterns of fire

activity, size, and shape that are likely related to social and cultural dynamics. First, the data indicate greater fire activity surrounding the international border. Specifically, number of fires and area burned was greatest on some of the Sky Islands that traverse the border or are adjacent to it, particularly the Peloncillo-Pan Duro, Huachuca-Patagonia, and Atascosa-Cibola ranges. This pattern is likely associated with greater human-caused ignitions along major travel corridors. Two of the largest fires that burned during dry 2011, the Horseshoe II Fire and Murphy Complex, were determined to be human-caused by the US Forest Service. Some unique fire patches and patterns occurred near the international border where lack of fuel continuity along the border access road or direct fire suppression resulted in long, straight fire perimeter edges adjacent to the boundary line. These uniquely shaped border fires were characterized by high eccentricity index values (*i.e.*, long and thin) and had strong east to west bearings. Alternatively, fires can be oriented in a particular direction due to prevailing winds during burning, or corresponding to topographic characteristics (Barros *et al.* 2013).

Secondly, population density was generally similar between burned and unburned sites, with a greater distribution of fires in the low population density range, but with a somewhat bimodal distribution showing a slight increase in fires occurring in the high population density range, indicating the influence of land use and anthropogenic activities on fires for some Sky Islands (Fig. 6g). Remote forests experienced proportionately more fire, suggesting that wildfires dominate the fire regime, rather than human use of fire in agricultural practices (*i.e.*, in Populated Forests; Fig. 5; Perez-Verdin *et al.* 2014). Furthermore, natural ignition source (*i.e.*, lightning strikes; Fig. 6f) did not limit the occurrence of fire, but areas in the southern Sky Islands with highest strike rate experienced less fire, possibly due to more mesic vegetation types and higher fuel moisture in those islands that receive more precipitation from the south.

Research implications and research needs

Dendrochronological fire scar evidence from many sites in northwestern Mexico shows that some forests have maintained historical fire regimes (Kaib 1998, Stephens *et al.* 2003, Yocum Kent *et al.* 2017) and can become reference sites for Western forests in the US that experienced long-term suppression (Leopold 1937, Fulé *et al.* 2012, Meunier *et al.* 2014), potentially guiding ecological restoration of altered sites (Stephens and Fulé 2005). Future research on modern fires in the Madrean Sky Islands could more directly consider the role of historical land use, forest management, and climate on fire attributes in this region. For example, the fire regional severity data (*i.e.*,

dNBR) that we developed to map fire perimeters, as measured using pre- and post-fire differencing of satellite imagery, could be used to examine the role of climate, fire weather, management history, and active fire management (*e.g.*, back burns) in resulting spatial heterogeneity of severity patterns. Research into land use history of individual Sky Islands would help to elucidate these possible effects, as would more stand-level field data describing historical fire regimes and current forest structure in sites with different fire histories in northern Mexico.

Conclusions

The purpose of this research was to fill a significant information gap on recent wildfire activity across the bi-national Madrean Archipelago Ecoregion of the United States and Mexico. Past fire research in this region, in particular tree-ring research, suggests that different fire regimes observed in mountains of the US and Mexico were linked to historical land use and fire suppression activities. Understanding the links between these environmental histories and contemporary fire regimes of the Sky Islands can help to guide regional fire planning, fuels management, and habitat conservation efforts on both sides of the US–Mexico border.

Our results show increasing fire sizes across the region, particularly in Sky Islands of the US, with large fires occurring during recent twenty-first century droughts. Area burned generally increased over the study period, culminating with the 2011 fire year, when the Horseshoe II Fire burned much of the Chiricahua Mountain range in Arizona. Number of fires and area burned were greatest on some of the mountains that traverse the border or are adjacent to it, suggesting that recent fire patterns in this area are strongly influenced by patterns of human activity. Two of the largest fires that burned during our study period, the Horseshoe II Fire and Murphy Complex, were determined to be human-caused by the US Forest Service and occurred during the dry 2011 fire season. Given projections of increasing temperature and decreasing precipitation (Wilder *et al.* 2013), along with projections of continued human population growth (Villarreal *et al.* 2013) in the borderlands region, large and more frequent fires may become more common in the future. Further analyses of fire occurrence and fire severity in the context of interactions among past and current land uses, regional and local climate variables, and fuel conditions can provide additional important information when considering scenarios of possible future fire regimes in this biologically and culturally diverse region.

Our research provides insight into the modern fire regimes of mountains in the Madrean Archipelago

Appendix

Table 4 Anderson-Darling statistical output for comparisons of burned and unburned samples (see Fig. 6 and Table 3), for the Madrean Ecoregion Sky Islands, US and Mexico. The standard deviation for the Anderson-Darling test statistic (AD.T) was 0.76, and the null hypothesis that all samples came from a common population was rejected in all comparisons ($P < 0.001$). Variables with density plots in Fig. 6 are shown in bold. Number of ties refers to the number of times identical values occur in the data. If too many ties occur, there will be a rejection of the null hypothesis and the result will suggest non-normality

Variable	US		Mexico	
	number of ties	AD.T	number of ties	AD.T
Road density	12091	144.57	23579	240.86
Population density	4189	114.84	8005	406.53
Terrain ruggedness	4092	466.68	7980	718.02
Lightning flash date	12191	358.16	23579	583.9
AHM	0	1203.7	0	1995.4
bFFP	486	753.27	598	2913.2
CMD	0	894.15	0	2690.6
DD_0	832	829.36	2171	2761.7
DD_18	0	881.7	0	2982
DD18	0	960.42	0	3239.8
DD5	0	934.04	0	3150.1
eFFP	1453	666.9	2233	2447.1
EMT	199	677.34	85	2367.5
Eref	2	607.38	0	3172.2
EXT	51	981.68	113	3069.2
FFP	216	736.15	256	2748.7
MAP	4	1079.3	2	528.65
MAT	194	932.23	141	3137.8
MCMT	539	786.1	251	2530.3
MSP	5	1021.7	28	128.37
MWMT	78	986.16	105	3035
NFFD	348	705.34	666	2678.3
PAS	6472	1118.2	17124	3853.6
PPT_sm	25	972.95	51	78.771
PPT_wt	144	569.68	263	1061.5
RH	3831	59.104	13584	23.661
SHM	0	1134.5	0	1137.3
Tave_sm	93	972.75	103	3190.6
Tave_wt	481	820.88	228	2721.8
TD	485	451.81	1111	134.93

Ecoregion, an area that previously lacked cross-border fire information. A major obstacle to our understanding of the connectivity of ecological, hydrologic, and socio-cultural systems in this region is geospatial data that adhere to political boundaries rather than natural ecological or physical boundaries. Recent research on ecosystem service flows in the US–Mexico borderlands highlights the challenges and importance of a transboundary approach (López-Hoffman *et al.* 2010, Norman *et al.* 2012, Norman *et al.* 2013). Transboundary data are particularly important to consider when managing habitat for migratory species and large predators (e.g., *Panthera onca*, Linnaeus; McCain and Childs 2008, Atwood *et al.* 2011), and for many other ecological processes that are not confined to political boundaries. An increased focus on developing and sharing transboundary datasets can contribute to collaborative research efforts between countries that improve knowledge about ecological patterns and processes in the borderlands, and support long-term regional planning and restoration efforts.

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Availability of data and materials

The dataset supporting the conclusions of this article is available in the ScienceBase-Catalog repository, <https://doi.org/10.5066/F76Q1WJ1>.

Authors' contributions

MLV, SLH, JMI, and CCM conceived and designed the study. MLV developed the mapping approach and TBP contributed major effort in identification of fires, digitizing perimeters, image processing, and accuracy assessment. MLV and SLH analyzed and interpreted fire patterns and environmental data. All authors participated in writing the paper; JMI and CCM made significant contributions to writing the study area and fire history descriptions, as well as providing insightful discussion. All authors read and approved the final manuscript.

Ethics approval and consent to participate

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Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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