

## Habitat distribution modeling reveals vegetation flammability and land use as drivers of wildfire in SW Patagonia

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**Abstract.** Despite important recent advances in modeling current and future global fire activity in relation to biophysical predictors there remain important uncertainties about finer-scale spatial heterogeneity of fire and especially about human influences which are typically assessed at coarse-spatial resolutions. The purpose of the current study is to quantify the influence of biophysical and anthropogenic variables on the spatial distribution of wildfire activity between 1984 and 2010 over an extensive southern Patagonian-Andean region from ca. 43° to 53° S extending from coastal rainforests to xeric woodland and steppe.

We used satellite imagery to map all detectable fires >5 ha from 1984 to 2010 in four study areas (each of 13,100 to 36,635 km<sup>2</sup>) and field checked 65 of these burns for accuracy of burned vegetation class and fire perimeters. Then, we used the MaxEnt modeling technique to assess the relationships of wildfire distributions to biophysical and human environmental variables in each of the four regions. The 232 fires >5 ha mapped in the four study areas accounted for an area of 1,314 km<sup>2</sup> indicating that at least 1.8% of the total area burned between 1984 and 2010. In general, areas with intermediate productivity levels (e.g., shrublands) have higher fire probability compared with areas of low and high productivity levels, such as steppe and wet forests, respectively. There is a marked contrast in the flammability of broad vegetation classes in determining fire activity at a regional scale, as well as a strong spatial relationship of wildfires to anthropogenic variables. The juxtaposition of fire-resistant tall forests with fire-prone shrublands and woodlands creates the potential for positive feedbacks from human-set fires to gradually increase the flammability of extensive landscapes through repeated burning. Distance to roads and settlements were also strong predictors, suggesting that fire in all regions is ignition-limited. However, these anthropogenic predictors influenced probability of fire differently among study regions depending on their main land-use practices and their past and present socioeconomic contexts.

**Key words:** human-ignition; Landsat; MaxEnt; *Nothofagus*; shrubland; spatial fire prediction; vegetation flammability; wildfire.

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## INTRODUCTION

There is growing recognition of the importance of changes in global fire activity as a consequence of climate change as well as an agent of land cover change with potential positive feedbacks of additional greenhouse gases into the atmosphere (Bowman et al. 2009). Studies that have addressed recent and future spatiotemporal variability of fire at global scales stress the need for holistic approaches that consider both biophysical and anthropogenic predictors of fire activity (Chuvieco et al. 2008, Moritz et al. 2012). At a global scale at coarse spatial resolutions (e.g., grid cells of  $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude), studies based on short (i.e., 2001 to 2007 or 2009) remotely-sensed records of fire activity support the varying constraints hypothesis which systematically relates fire activity to gradients of biomass resources to burn and atmospheric conditions suitable to burning (Krawchuk and Moritz 2011). However, global scale analyses do not effectively incorporate anthropogenic factors that may affect ignition frequency, fire suppression and other land use effects on fire activity (Moritz et al. 2012). At a global scale, fire activity has been shown to be sensitive to socioeconomic variables such as population density and gross domestic product but the coarse-scale resolution (either from  $0.5^\circ$  grids or country level) of these variables precludes a mechanistic understanding of how human factors affect fire activity (Chuvieco et al. 2008, Aldersley et al. 2011). An improved understanding integrating both biophysical and human drivers of fire activity requires analyses over large areas of biophysical and socioeconomic heterogeneity but at a fine-scale spatial resolution ( $\sim 1 \text{ km}^2$ ) and over multi-decadal time periods. To date such studies exist only for parts of North America (e.g., Parisien et al. 2012) where spatially explicit records of fire activity over the past several decades are available from government-sponsored databases. In the current study, for an area of ca.  $100,000 \text{ km}^2$  in southwestern South America we develop a spatially explicit fine-scale resolution record of wildfires from 1984 to 2010 with Landsat satellite imagery (30-m spatial resolution) to examine spatial relationships of fire activity to biophysical and human explanatory variables.

Environmental controls of fire ignition and

spread vary in their relative importance and interact differently depending on characteristics of the biome, climate conditions, and the influences of humans (Krawchuk et al. 2009, Aldersley et al. 2011). Analyses conducted at both global and regional scales show that fire activity peaks at intermediate locations along productivity/aridity gradients with reduced fire activity towards the extremes of dry low-productive ecosystems and in continuously moist or high-productive ecosystems (Pausas and Bradstock 2007, Holz et al. 2012b; Pausas and Ribeiro, *in press*). Thus, global warming is likely to have contrasting effects on fire regimes in different biomes (Moritz et al. 2012) but effects of finer-scale spatial biophysical heterogeneity and of human factors remain poorly understood for large regions. Regional scale analyses that span substantial gradients of bioclimatic conditions while still permitting a mechanistic understanding of how human factors affect fire occurrence, offer a connection between coarse-scale global scale studies and fine-scale studies limited to a single biome type or single socioeconomic context. Coarse-scale studies are dependent on aggregated socioeconomic data across large heterogeneous areas, such as entire countries (e.g., Chuvieco et al. 2008, Aldersley et al. 2011) that obfuscate the processes by which human factors affect fire activity in different biophysical settings. In contrast, most fine-scale studies, by being limited to a small range of fuel types and socioeconomic conditions (e.g., Kennedy and McKenzie 2010), have unknown applicability across a broader range of biome types or in different socioeconomic contexts.

While coarse-resolution analyses of fire activity based on satellite-derived burned area maps are providing important insights into the relative importance of biophysical factors driving fire, there is a strong consensus that existing studies are limited by: (1) inability to distinguish wildland fires from agricultural burning (LePage et al. 2010, but see Magi et al. 2012); (2) partial understanding of mechanistic relationships of fire to biophysical predictors due to the  $0.5^\circ$  spatial resolution of most studies (e.g., Krawchuk and Moritz 2011; Pausas and Ribeiro, *in press*); (3) short records (typically  $< 8$  years) of fire in studies based on satellite imagery that preclude the inclusion of a sufficient number of fires for

certain regions or robust estimates of mean fire occurrence in some biophysical settings (Chuvieco et al. 2008); and (4) aggregation of socioeconomic data across large areas which obscures mechanisms by which humans actually affect fire regimes (Aldersley et al. 2011). Fire data acquired at finer spatial resolution and extending over longer time periods is required for development of a more robust quantitative understanding of the relationships of wildland fire activity to biophysical and anthropogenic factors. However, such data are available for only a few areas and mostly for temperate ecosystems in North America and Europe (e.g., Parisien and Moritz 2009). For southern South America fine-resolution spatial datasets of area burned are not currently available for large regions, and consequently analyses of factors that drive fire activity over extensive areas must contend with the need to develop original datasets of area burned.

In Patagonia, climate as well as many land-use and socioeconomic trends are increasingly becoming more conducive to fire (Veblen et al. 2011). Given projected future climate changes, such as the positive trajectory of the Southern Annular Mode (SAM) and its associated teleconnection to warm and dry climate trends in southern South America (Thompson et al. 2011), wildfire activity in western Patagonia is expected to increase during the 21st century (Holz and Veblen 2011b). In addition, current trends in land use, such as the expansion of plantations of fire-prone exotic conifers (mainly *Pinus contorta* and *P. ponderosa*) (Veblen et al. 2011) as well as the mismanagement of fire by farmers and the intentional ignition of wildfires as an expression of social unrest (De Torres Curth et al. 2012, Marini 2012) also portend increased fire activity. Because most fires are either purposefully or accidentally ignited by people in western Patagonia (Veblen et al. 2011), human presence is crucial in determining fire risk. Potentially, human presence in an area could either increase ignition frequency or decrease fire spread through greater vigilance and fire suppression. Following global trends, residential use of the wildland urban interface (WUI) in Patagonia is expanding as is the quality and extent of the road network that now facilitates access to previously remote areas. Additionally, tourist activities are steadily increasing in numerous localities in

Patagonia, including areas that were inaccessible for most tourists only two decades ago (Martinic 2005). These recent changes in human population, socioeconomic activities and transportation infrastructure have the potential to increase the frequency of human ignitions in large parts of Patagonia. Consequently, to support decision making in fire management and planning at local to regional scales, spatially explicit knowledge is needed of the associations of fire activity with biophysical and anthropogenic variables across the range of Patagonian ecosystems from temperate rainforests in the west to xeric woodlands at the ecotone with the Patagonian steppe in the east.

Studies evaluating the susceptibility of different landscapes to fire in southern South America began only recently and are limited to northwestern Patagonia, in Argentina (40° to 43° S). In particular, the only study in the region that modeled fire probability across space was conducted at a landscape scale (i.e., 7,800 km<sup>2</sup>) and employed a relatively small fire dataset (18 fires) (Mermoz et al. 2005). This landscape-scale study found that vegetation class is one of the most important variables in determining probability of fire. Specifically, post-fire shrublands are more susceptible to subsequent fires than mature and tall *Nothofagus* forests, suggesting the existence of positive feedbacks toward enhanced fire activity due to the replacement of fire-resistant tall forests with fire-prone shrublands (Mermoz et al. 2005, Veblen et al. 2011, Kitzberger et al. 2012). In addition, fire activity in northwestern Patagonia has been shown to be higher closer to human settlements and roads independently from vegetation class (Mermoz et al. 2005, Gowda et al. 2012). Despite these initial contributions for a relatively small area in northwestern Patagonia, there still is a lack of regional-scale understanding of the heterogeneity of spatial fire ecologies and their intrinsic differences (e.g., fuel-limited versus drought-limited) across a steep precipitation gradient in an extensive area of temperate ecosystems in southwestern South America (>250,000 km<sup>2</sup>).

The primary goal of the current study is to quantify the influence of biophysical and anthropogenic variables on the coarse-scale distribution of wildfire activity between 1984 and 2010 over the extensive southern Patagonian-Andean re-

gion from ca. 43° to 53° S. We evaluated the biophysical and human “environmental space” of wildfire in this Patagonian region to determine which predictor variables best explains the spatial distribution of wildfire activity during the study period.

We expect fire probability to be well predicted from biophysical variables, such as vegetation type and position along climatic gradients, but the strength and pattern of anthropogenic influences are likely to vary according to predominant land-uses. Humans can increase burn area through increased accidental or intentional ignitions but they can also decrease it through fire suppression or fuel reduction resulting from livestock grazing. To determine differences in fire activity and probability to burn across extensive biophysical gradients, we used Landsat satellite images to map all detectable fires >5 ha from 1984 to 2010 in four regions (each of 13,100 to 36,635 km<sup>2</sup>) in southwestern Patagonia. To assess the relationships of wildfire distributions to biophysical and human environmental variables we used the MaxEnt modeling technique (Phillips et al. 2006), which has been successfully used in fire spatial modeling applications (Parisien and Moritz 2009, Moritz et al. 2012).

## MATERIALS AND METHODS

### Study area

The area of interest extends from ca. 42°50' to 53°30' S and from ca. 70°40' to 74°30' W along the Patagonian Andes. Poleward along this latitudinal gradient, mean annual temperature declines and annual precipitation becomes more evenly distributed seasonally. The climate of southwestern South America is dominated by air masses coming from the Pacific and the storm tracks in the westerly winds which predominate year round. Wildfires generally occur during the summer season of warmer and drier weather, which is shorter, cooler and wetter poleward. The Andean range causes abundant orographic precipitation that sharply declines to the east. In the northern portion of the study area (ca. 43° to 47° S) this precipitation pattern is largely responsible for the abrupt transition from the humid Valdivian and Northern Patagonian rainforests near the Pacific coast to the dry Patagonian steppe on the eastern foothills of the Andes (Veblen et al. 1996).

South of ca. 47° S the precipitation gradient is even steeper (Aravena and Luckman 2009) where Magellanic forests and moorlands (poorly drained heathlands) in the west are replaced by Patagonian steppe to the east of the Andes (Pisano 1981).

Within this broad area of interest, four study areas (named Chiloé-Chonos [CC], Chubut-Lagos [CL], Aysén [AY], and Magallanes [MA]) were defined for purposes of fire mapping and analysis based on their relatively distinct biophysical (Amigo and Ramirez 1998, Luebert and Pliscoff 2006) and socioeconomic (INDEC 2001, INE 2002) conditions (Table 1). For each of these areas the availability of cloud-free satellite imagery was suitable for comprehensive mapping of wildfire activity over the 1984–2010 period (see *Fire mapping* below; Fig. 1). These four regions represent a north-to-south gradient of decreasing temperature and annually less frequent weather conditions suitable for wildfire (Holz et al. 2012b). The three northern study areas are separated from the southernmost study area by ca. 200 km corresponding to the Southern Patagonian Ice Field (Fig. 1).

Although natural fires ignited by lightning are not believed to have been sufficiently frequent in southwestern Patagonia to be a major selective influence on plant traits, some modern as well as apparently early Holocene lightning-ignited fires have occurred even in the western rainforests (Holz et al. 2012a). Lightning-ignited fires may not be an important driver of vegetation dynamics in southwestern Patagonia, but anthropogenic fires have had major influences on vegetation patterns throughout this region. Wildfires in southwestern Patagonia set by the aboriginal population were relatively common before Euro-American settlers arrived. There is ethno-historical evidence of various uses of fire, from slash and burn agriculture in Chiloé (Torrejón et al. 2004), to guanaco (*Lama guanicoe*) hunting in the steppe ecotone (Musters 1871). In conjunction with permanent Euro-American settlement beginning in the late 19th to early 20th centuries there was a pulse of widespread intentional forest burning in most of southwestern Patagonia (Veblen et al. 2008, Holz and Veblen 2011a). The main reason for settlers to burn forests was to open the land for raising livestock, but burning was also practiced to facilitate timber extraction in some places. After the large-scale forest

Table 1. Physical and socioeconomic characteristics of the study areas. Temperatures (T°) are approximate mean values at low elevation areas for comparative purposes among regions. Mean annual precipitation (pp) range refers to the spatial variation within each study region, again for stations at low elevation. Road network descriptions are relative to the other study areas in the region.

Characteristic	Chonos-Chiloé	Chubut-Lagos	Aysén	Magallanes
T° coldest month (Jul.) (°C)	6	4	3	2
T° warmest month (Jan.) (°C)	14	15	14	11
Mean annual pp range (mm)	2000–3000	500–2000	200–2000	400–1500
Human population (% urban)	20,000 (50%)	50,000 (90%)	10,000 (10%)	140,000 (95%)
Principal land uses†	SA, AF, TE, SF	LR, TO	MI, LR, TE, TO	LR, TO
Road network	sparse; almost absent in the archipelago	dense	sparse	dense eastwards, almost absent westwards

Note: Information sources: temperature and precipitation (Schneider et al. 2003, Hijmans et al. 2005), human population (INDEC 2001, INE 2002), land use (Martinić 2002, 2005, Bornschlegl 2011), road network (SIGN250, Digital Chart of the World, Dirección de Vialidad Chile).

† SA: subsistence agriculture; AF: artisanal fishing; TE: small scale timber extraction; SF: salmon farming; LR: livestock raising; TO: tourism; MI: mining.

burning period lasting from the late 1800s to the mid-1900s, depending on the region, national policies of fire suppression were adopted and continue to be implemented with varying degrees of effectiveness across the study area (Veblen et al. 2008). Throughout southwestern Patagonia, although humans are the most common source of ignitions, fire spread and variability in annual area burned is determined primarily by annual climate variability (Holz et al. 2012b).

*Chiloé-Chonos study area.*—The CC study area encompasses the southern portion of the Chiloé Island (from ca. 43° S) and the Chonos Archipelago (excluding the southernmost islands) on the west side of the Andes (Figs. 1, 2A). The topography of this region consists mostly of channels and islands with gentle hills originated by glacial erosion. Located in southern part of the Valdivian rainforest and the northwestern portion of the Northern Patagonian forest districts, this area is characterized by dense stands of evergreen broadleaved trees (e.g., *Nothofagus dombeyi*, *N. nitida*, *N. betuloides*, *Weinmannia trichosperma*, *Drimys winteri*, *Tepualia stipularis*) mixed with evergreen conifers (e.g., *Saxegothaea conspicua*, *Podocarpus nubigena*, *Pilgerodendron uviferum*; Fig. 1; Gajardo 1995). The southwestern part of this study area where the oceanic influence is greatest is characterized by moorland of small scattered trees and dwarf shrubs, cushion plants, and mosses (e.g., *Sphagnum* spp.), often forming blanket peat. Over the past ca. 150 years both, Chiloé and the Chonos

Archipelago experienced widespread forest burning to facilitate timber extraction primarily of *P. uviferum* (Donoso and Lara 1995, Holz and Veblen 2011a).

*Chubut-Lagos study area.*—The CL study area, spans the Andes from ca. 43° S to 45° S but is mostly on the east side of the Andes (Figs. 1, 2B). It is characterized by rugged topography in its western portion and by low foothills in its easternmost areas (Fig. 2B). Vegetation in the far western portion of this region is mesic evergreen forest dominated by *Nothofagus dombeyi* and *N. betuloides*. Higher elevations along the western and central portions of the gradient are characterized by deciduous forests of *N. pumilio*. The eastern foothills bordering the Patagonian steppe of bunchgrasses and low shrubs are characterized by woodlands of the shrubby tree *N. antarctica* and other small trees or shrubs, such as *Schinus patagonicus* and *Lomatia hirsuta* (Veblen et al. 2008). Open woodlands of the conifer *Austrocedrus chilensis* are common near the steppe ecotone in the northern portion of the study area. Large-scale forest burning and clearing to open the landscape for livestock raising occurred primarily during the 1890s and early 1900s (Willis 1914). For instance, an estimated area of 275,000 ha burned in 1943–1944 in the Andean area of the province of Chubut, an area of ca. two million ha that includes the eastern portions of the CL study area (Tortorelli 1947).

*Aysén study area.*—The AY study area occurs entirely within the Chilean administrative district

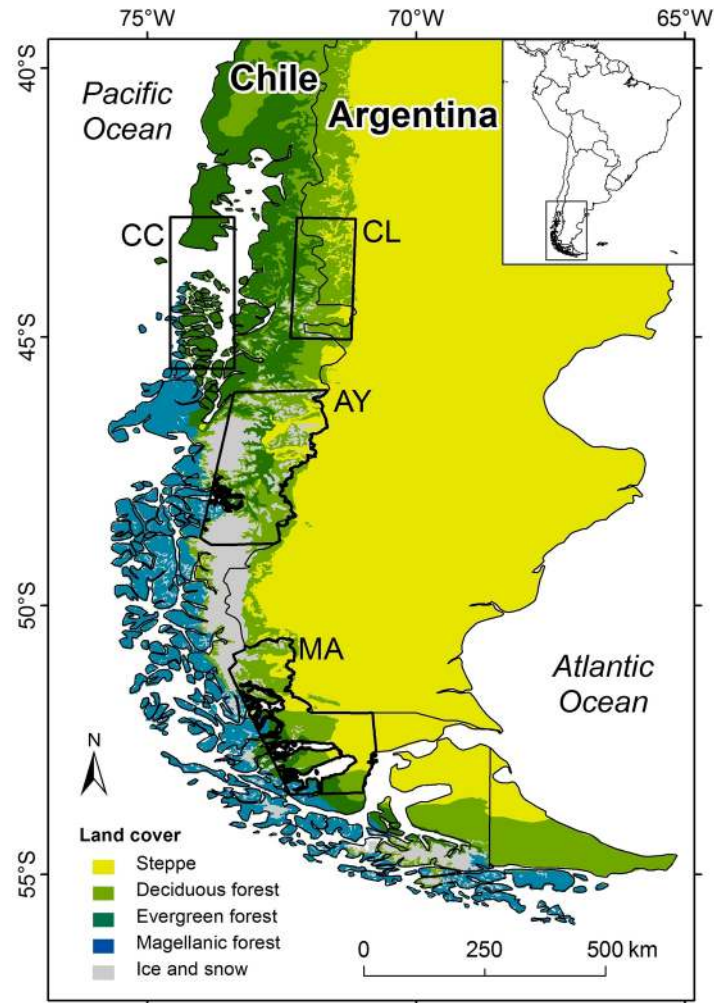


Fig. 1. Map showing the location and extent of each of the four study areas (Chiloé-Chonos, CC; Chubut-Lagos, CL; Aysén, AY; and Magallanes, MA), and the distribution of the major vegetation and land cover types. Distribution and extent of vegetation classes is modified from Lara et al. (1999).

of Aysén, and extends from 46° S southwards to ca. 49° S to the northern end of the Southern Patagonian Ice Field. To the west this study area is bordered by fjords, the ocean and the Northern Patagonian Ice Field, and to the east by the Chilean-Argentine border (Figs. 1, 2C). It is characterized by rugged glacial topography in the west that gives way to low foothills towards the east. The western part of the gradient is characterized by the North Patagonian rainforest dominated by evergreen broadleaved trees, such as *Nothofagus betuloides*, which to the east give way to deciduous *N. pumilio* and *N. antarctica* forests and woodlands, and eventually to steppe

(Veblen et al. 2008). Widespread forest burning and clearing for establishing a livestock economy occurred primarily during the 1930s to 1950s and resulted in conversion of large tracts of *N. pumilio* forest to anthropogenic shrublands and grasslands (Martinic 2005).

*Magallanes study area.*—The MA study area is located within the southernmost Chilean administrative district of Magallanes, mostly on the east side of the Andes. Latitudinally, it extends from the southern end of the Southern Patagonian Ice Field at Torres del Paine National Park (50°30' S) to the northern portion of the Brunswick Peninsula, 45 km north from the Magellan Strait

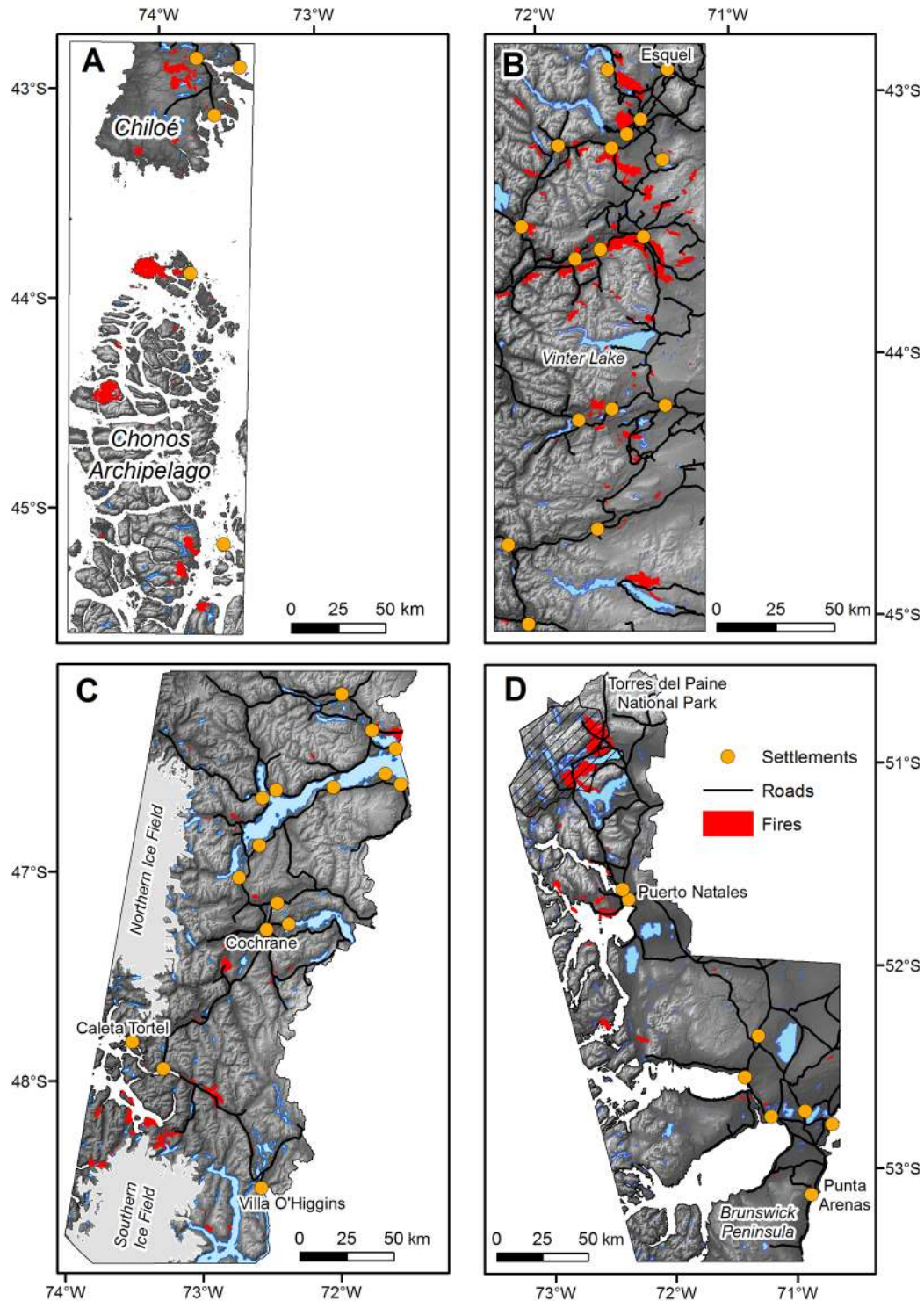


Fig. 2. Distribution and extent of mapped fires (1984–2010), location of human settlements and road networks, and topography in (A) CC (Chiloé-Chonos), (B) CL (Chubut-Lagos), (C) AY (Aysén), and (D) MA (Magallanes) study areas. Legend in (D) applies to all panels. The area of Torres del Paine National Park is indicated by crosshatching in (D).

(53°30' S); and from west to east, it extends from the eastern edge of the coastal archipelago to the Chilean-Argentine border (Figs. 1, 2D). The vegetation of the island archipelago and westernmost peninsulas is a mosaic of moorland, small patches of evergreen *Nothofagus* forest, and boggy woodlands of *Pilgerodendron uviferum*. On the mainland, the evergreen Magellanic forest dominated by *N. betuloides* and *Drimys winteri* extends eastward until precipitation drops below ca. 800 mm where it gives way to deciduous forests and shrublands dominated by *N. pumilio* and *N. antarctica* and eventually steppe (Luebert and Plissock 2006). Pollen and charcoal records in southern Patagonia indicate that fire was relatively infrequent in this landscape, and began to increase in frequency as early as 1600 A.D. with initial European contact and possibly the aboriginal adoption of horses for hunting purposes in the woodland-steppe region (Huber and Markgraf 2003). Forest burning associated with sheep ranches in the area of *N. pumilio* forests and woodlands of *N. antarctica* was widespread especially during the late 19th century (Huber and Markgraf 2003).

#### Fire mapping

In each of the study areas we mapped all fires >5 ha occurring from 1984 to 2010 detectable in cloud free TM, and ETM+ Landsat images obtained from the USGS Global Visualization Viewer (<http://glovis.usgs.gov/>) covering the area from 42°30' S to 54° S and from 70° W to 74° W. The images cover a surface area of ca. 340,000 square kilometers, and total 14 image frames and 128 scenes (mean of  $9.1 \pm 0.5$  SE scenes per image frame, maximum of one scene per year). Imagery was not uniformly available for all years (e.g., for 1988–1998 for many areas), but the frequency of available years of imagery was sufficient for mapping fires. Because burned vegetation is most evident in Landsat imagery during the snow-free growing season (September to March), we only selected images acquired during those months. We conducted systematic visual surveys of all Landsat scenes and identified burns by using pre- and post-fire dates in false-color composite images displaying bands 3 (red), 4 (near infrared), and 7 (short-wave infrared) in the blue, green and red channels, respectively. This false-color composite combina-

tion has been successfully used to visually detect and map fire perimeters in similar vegetation classes as those present in our study areas (Mermoz et al. 2005). We subsequently mapped all detected fires using a supervised maximum likelihood classification and exported into a GIS as polygon layers. Because Landsat scenes were scarce for some time periods, such as most of the 1990s, there is the chance that we underestimated fire occurrence in grasslands due to rapid regrowth of vegetation cover in these areas. For burns in other woody vegetation types, field observations of re-growth following fires of known dates leads to the conclusion that we successfully identified nearly all fires >5 ha in the areas surveyed. A total of 232 burns were mapped at a 30-m spatial resolution within the four defined study areas. We field checked fire boundaries, extent and type of burned vegetation for 65 fires (i.e., 25% of the total burns) using a Mobile Mapper (Magellan) GPS device and ArcPad 7.1 GIS software (ESRI 2008) to test positional accuracy.

#### Predictor variables

Based on previous research in similar vegetation classes (Mermoz et al. 2005) and availability of data for our four study areas we selected eight predictor variables (Table 2), including one biotic variable (vegetation), five abiotic variables (mean annual precipitation, mean summer temperature, elevation, slope aspect, and slope angle), and two anthropogenic variables (distances from roads and settlements). We chose mean annual precipitation (rather than seasonal precipitation) because it is an indicator of productivity and hence of available biomass to burn. Summer temperature is a strong indicator of suitable weather conditions for fire spread during the predominantly summer fire season.

Vegetation classes were based on a 1:500,000 digital vegetation map of the Valdivian Ecoregion (Lara et al. 1999). Because this map does not extend to the Magallanes study area, for this study area we used the vegetation classes from the Chilean Forest Service (CONAF et al. 1999) that we reclassified into new classes to match those of the Valdivian Ecoregion map. Although not ideal for fine-scale studies, the spatial resolution of these two sources of vegetation maps is adequate for the regional scale of our



Table 2. Description of the predictor variables of wildfire activity and data sources for each one.

Predictor variables	Description	Source
Vegetation	Classes of vegetation and land cover	Valdivian Ecoregion (Lara et al. 1999) and Catastro de Recursos Vegetacionales Nativos (CONAF et al. 1999)
Precipitation	Mean annual precipitation (mm; 1950–2000)	WorldClim (Hijmans et al. 2005)
Temperature†	Mean summer (Dec–Feb) temperature (°C; 1950–2000)	WorldClim (Hijmans et al. 2005)
Elevation	Elevation above sea level (meters)	Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM Version 4)
Aspect†	Slope aspect (azimuth)	Derived from the DEM (SRTM Version 4)
Slope†	Slope angle (degrees)	Derived from the DEM (SRTM Version 4)
Roads	Euclidean distance from roads	Calculated from digital road maps (SIGN250, Digital Chart of the World, Dirección de Vialidad Chile)
Settlements	Euclidean distance from human settlements	Calculated from digital maps of human settlements (SIGN250, Instituto Nacional de Estadísticas, Chile)

† Not used in the final model.

analyses (i.e., 1 km grid size). Both vegetation maps were created using Landsat scenes, mostly from the mid-1980s and some from the mid-1990s, and from aerial photos from the mid-1990s (CONAF et al. 1999, Lara et al. 1999). Therefore, for fires that occurred prior to the mid-1990s we verified, and corrected if necessary, the accuracy of pre-fire vegetation in the maps using pre-fire Landsat images and field observations. Elevation, slope angle and aspect were derived from the 90m-resolution Digital Elevation Models (DEM) from the Shuttle Radar Topography Mission (SRTM Version 4; <http://srtm.csi.cgiar.org/>). Mean annual precipitation and mean summer (Dec–Feb) temperature were obtained from the 1-km global climate gridded WorldClim dataset (Hijmans et al. 2005). GIS layers of roads and human settlements for Argentina were obtained from a 1:250,000 digital map (SIGN250; Instituto Geográfico Nacional, Argentina). For Chile, these data were obtained from the 1:1,000,000 Digital Chart of the World (1992) and from digital maps of the Chilean Roads Administration (Dirección de Vialidad) and the Chilean National Statistics Institute (INE); and were verified and corrected using the virtual globe interface Google Earth and field observations. The roads layer includes main and secondary roads and some private access roads. We computed raster surfaces of Euclidean distances from roads and settlements in each region including features located outside the study areas at a buffer distance of ca. 20 to 50 km from the edge. Despite some population growth and improvement of the road network during the

study period, the overall spatial configuration of human settlements and roads has remained relatively unchanged with the exception of the construction of some new roads in southern AY during the late 1990s.

#### *Modeling spatial probability of fire occurrence*

We used the MaxEnt program (Phillips et al. 2006, Elith et al. 2011) to model the probability of fire occurrence across space and to explore the predictive power of the selected environmental variables on fire probability separately for each of the four study areas. Originally designed for modeling the spatial distribution of species from environmental variables (Phillips et al. 2006), the MaxEnt algorithm has been successfully applied to the spatial modeling of probability of fire occurrence at regional to global scales (Parisien and Moritz 2009, Moritz et al. 2012, Parisien et al. 2012). This algorithm uses presence-only data of the variable of interest (i.e., burned polygons) to compare the values of the environmental predictors associated with these presence points with those of a background consisting of the means of all values of the environmental variables over the entire study area. MaxEnt has proven to be more conservative than other models in predicting probability of species occurrence (Kumar et al. 2009), in part, because it adjusts for over fitting through a process of “regularization,” which prevents the algorithm from matching the observations too closely (Elith et al. 2011).

To avoid colinearity among predictor variables we conducted cross-correlations among variables

and removed those highly correlated with each other (i.e., Pearson correlation coefficient  $>0.6$ ). Thus, we excluded summer temperature from the modeling of fire probability for all study areas because of its high correlation with (and dependence on) elevation ( $R = 0.9$ ;  $P < 0.05$ ). To reduce spatial autocorrelation (Moran's  $I < 0.6$ ) while simultaneously maintaining an adequate resolution that preserves the spatial attributes of the fire layer, we used a grid cell size of  $1 \text{ km}^2$  for all variables. We resampled variables that were obtained at finer grid resolutions than  $1 \text{ km}^2$  using majority (vegetation and slope aspect) and bilinear interpolation (elevation and slope angle) algorithms (Wade and Sommer 2006, ESRI 2008). Finally, we extracted point values for all predictor variables and fire polygons using a systematically spaced  $1 \times 1 \text{ km}$  grid and we used these data for the MaxEnt models. The use of this grid resulted in the exclusion of some small fires from the analysis but does not affect the interpretation of the results at the regional scale because medium to large fires account for most of the area burned. Spatial data management and processing were conducted in ArcGis 9.3 (ESRI 2008) and fire probability models were computed in MaxEnt 3.3.3e (Phillips et al. 2006).

We evaluated the relative contribution of each environmental variable to the model using a heuristic estimate, which considers the increase or decrease in model gain, a measure of goodness of fit, that corresponds to each predictor variable during the iterative process of model training and is then transformed to a percentage (Phillips et al. 2006). The response of fire probability to each environmental variable was analyzed using response curves generated by the MaxEnt software. Response curve plots show fluctuations (i.e., from 0 to near 1) in the predicted logistic probability of conditions suitable for fire when the environmental predictor varies, while keeping all the other predictor variables at their average value over the set of presence points.

The MaxEnt output is based on fire data for the period 1984–2010. Therefore, temporal scale it is not considered in the model, which implies that the model does not evaluate specific conditions in a given year, such as interannual climate variability, to predict probability of fire. Instead, mapped probabilities represent the relative likelihood of fire activity over the entire analyzed

time period (Parisien et al. 2012).

### *Model evaluation*

Fire presence and predictor variable data were randomly partitioned into training (70%) and test (30%) datasets to evaluate the models for each of the four study areas. We used the area under the receiver operating characteristic (ROC) curve (AUC) to evaluate model discriminatory power. The AUC indicates how well the model maximizes true-positive and minimizes false-positive predictions, and is widely used as a threshold-independent evaluator of model performance (Fielding and Bell 1997). A model with an AUC close to 1 denotes perfect discrimination, whereas a model with an AUC of 0.5 is no better than random. Though the AUC curve was originally designed for presence and absence data, it can be adjusted for use with presence only data by substituting absences with a random sample of background values (Phillips et al. 2006). In order to assign a probability threshold to indicate areas of high or low probability of fire activity we used the maximum value for the sum of the sensitivity plus the specificity calculated for each region. This threshold selection criterion was used due to its efficiency in producing accurate predictions and its relative insensitivity to low prevalence values as is the case with our dataset (Liu et al. 2005, Jimenez-Valverde and Lobo 2007).

## RESULTS

### *Fire mapping*

The 232 fires  $>5 \text{ ha}$  mapped in the four study areas accounted for an area of  $1,314 \text{ km}^2$  indicating that at least 1.8% of the total area included in the study areas had burned in 1984–2010 (Table 3). The burned area ranged from 1.1% for the AY region to 2.6% for the CC region (Table 3). Field observations at 65 mapped fire locations consistently confirmed the vegetation class burned, as well as the accuracy of the mapped fire perimeters. Field observation of unburned vegetation at fire perimeters indicated a discrepancy with the pre-burn vegetation interpreted from the available vegetation map in only 8% of the burns. In ca. 95% of these cases, this disparity between actual and mapped pre-burn vegetation was due to spatial inaccuracies in the perimeters of mapped vegetation classes

Table 3. Extent of the study areas (excluding sea surfaces), area susceptible to burn, burned area (fires >5 ha; 1984–2010), number of mapped fires (>5 ha), and percent of ground-checked mapped fires. Area susceptible to burn indicates the extension of vegetation capable of burning in each study area excluding areas without fuels or significant amounts of it (e.g., lakes, glaciers, rocks, high Andean vegetation).

Study area	Total area surveyed (km <sup>2</sup> )	Area susceptible to burn (km <sup>2</sup> )	Burned area 1984–2010 (km <sup>2</sup> , %)	No. fires 1984–2010	Ground-checked fires (%)
Chiloé-Chonos (CC)	13,100	12,894	338 (2.6)	51	7.8†
Chubut-Lagos (CL)	22,200	19,392	440 (2.3)	97	40.2
Aysén (AY)	36,635	17,872	201 (1.1)	44	27.3
Magallanes (MA)	26,863	21,655	335 (1.5)	40	17.5
Total	98,798	71,813	1,314 (1.8)	232	28.0

† Only in Chiloé.

rather than misclassification of the entire vegetation polygon.

#### *Spatial probability of fire occurrence*

The area under the ROC curve (AUC) values (representing the model's discriminatory power) varied from 0.84 to 0.92 for the four MaxEnt models (Table 4). Thus, all four models performed well in maximizing true-positive predictions and minimizing false-negative predictions. Omission errors ranged from 9.1 to 19.6%, indicating that, at the probability threshold corresponding to the maximum value for the sum of the sensitivity plus specificity, 9.1 to 19.6% (depending on the region) of the actual fire locations were situated in areas predicted to be unsuitable for fire (i.e., false negatives). At these probability thresholds, the predicted percentage of area with high probability of fire in the test datasets ranged from 14.6 to 28.9% for the two northern areas (CC, CL) and from 7.9 to 13.3% for the two southern areas (AY, MA) (Table 4).

Based on the heuristic estimates of relative

contribution of each environmental variable to the model, predictor variables that contributed the most to the MaxEnt model predictions in the majority of the study areas were vegetation class, distance to settlements, and distance to roads. The percent contribution of vegetation class was high in three of the study areas: 44% in CL, 28% in AY, and 21% in MA (Fig. 3B–D). These three study areas all include the full gradient of vegetation classes from evergreen rainforest to steppe. In contrast, in the topographically and climatically more uniform CC study area, where the vegetation classes are mostly limited to evergreen forest and moorland, vegetation class contributed only 2% to the model (Fig. 3A). Precipitation contributions to the model were 20 and 26% in CC and MA, respectively, but only 11 and 12 in% in AY and CL, respectively (Fig. 3A–D). Elevation contributed less than 10% in CC and MA, but in CL and AY it contributed 14 and 33%, respectively (Fig. 3A–D). The range of elevation was substantially greater in the latter compared to the former two study areas (Fig. 4I–

Table 4. Performance measures for the MaxEnt models for each study area using the test dataset. Area Under the Curve (AUC) indicates the mean area under the receiver operating characteristic (ROC) curve (sensitivity vs. the predicted area (1 – specificity) plot) for the 20 replicate MaxEnt runs for each study area. The logistic threshold is the probability threshold corresponding to the maximum value for the sum of the sensitivity plus specificity. Predicted fire area is the percentage of the area susceptible to burn that is expected to have a high probability of fire activity given the indicated thresholds. Omission error indicates the percentage of actual fire points located in areas predicted to be unsuitable for fire (i.e., false negatives). All values correspond to test datasets.

Study area	AUC	Logistic threshold	Predicted fire area (%)	Omission error (%)
Chiloé-Chonos (CC)	0.92	0.277	14.6	12.5
Chubut-Lagos (CL)	0.84	0.292	28.9	16.3
Aysén (AY)	0.90	0.302	13.3	19.6
Magallanes (MA)	0.92	0.185	7.9	9.1

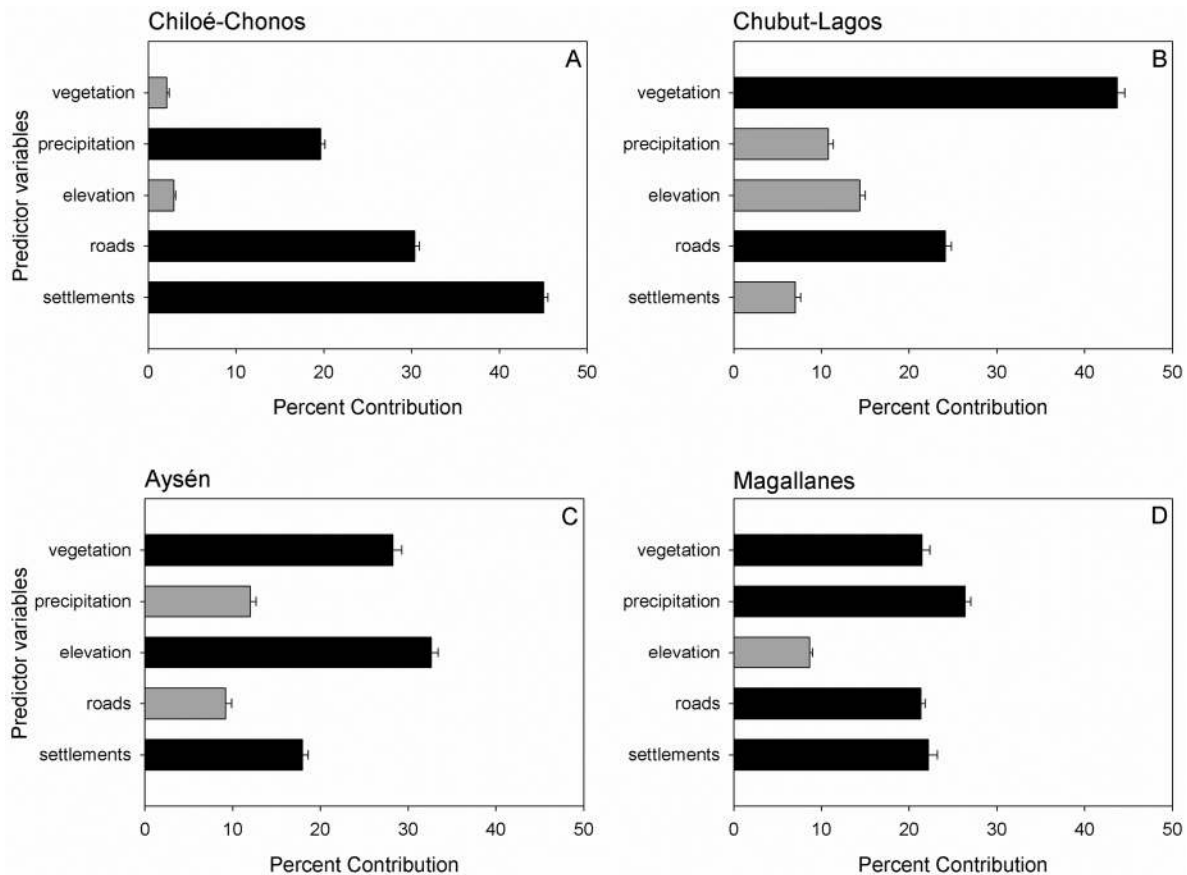


Fig. 3. Estimates of the relative contributions of the predictor variables to the MaxEnt models for each study area based on a heuristic estimate transformed into percentage. Values are averages and standard errors from 20 replicate runs. Black bars indicate percent contributions greater than 15%.

L). Distance to roads contributed 22, 24 and 30% in MA, CL and CC, respectively, but only 9% in AY. Distance to settlements contributed 18, 22, and 45% in AY, MA, and CC, respectively, but only 7% in CL (Fig. 3A–D). Slope angle and aspect did not contribute more than 6 and 2%, respectively, to any of the models and were not included in the final models.

Based on the response curves of fire probability to each environmental predictor variable, vegetation class affected the probability of fire in a consistent manner across CL, AY and MA study areas, where vegetation contributed  $\geq 21\%$  to the models (Fig. 4B–D). In these study areas, shrub-dominated vegetation classes and grasslands (including steppe) typically have higher probabilities of fire occurrence than tall forests dominated by *Nothofagus* spp. (Fig. 4B–D). For

example, in the CL study area along the xeric to mesic gradient, fire probabilities fall from a high range of 0.60 to 0.67 in the *N. antarctica* shrubland and anthropogenic shrub and grassland to a low range of 0.27 to 0.28 in the *N. pumilio* and the *N. betuloides* forests (Fig. 4B). In the AY study area, fire probability in tall *Nothofagus* forests is half or less the probability in the anthropogenic shrub and grass vegetation class (Fig. 4C). Similarly, in the MA study area the probabilities of fire in tall *Nothofagus* forests are ca. one third less than in the shrubland and mixed shrubland/grassland vegetation classes (Fig. 4D). Steppe in the MA study area also has a high probability of fire, whereas in the two northern study areas where steppe includes some areas of fuel-limited sparse vegetation the fire probabilities are lower. The consistently lower probability of fire in tall

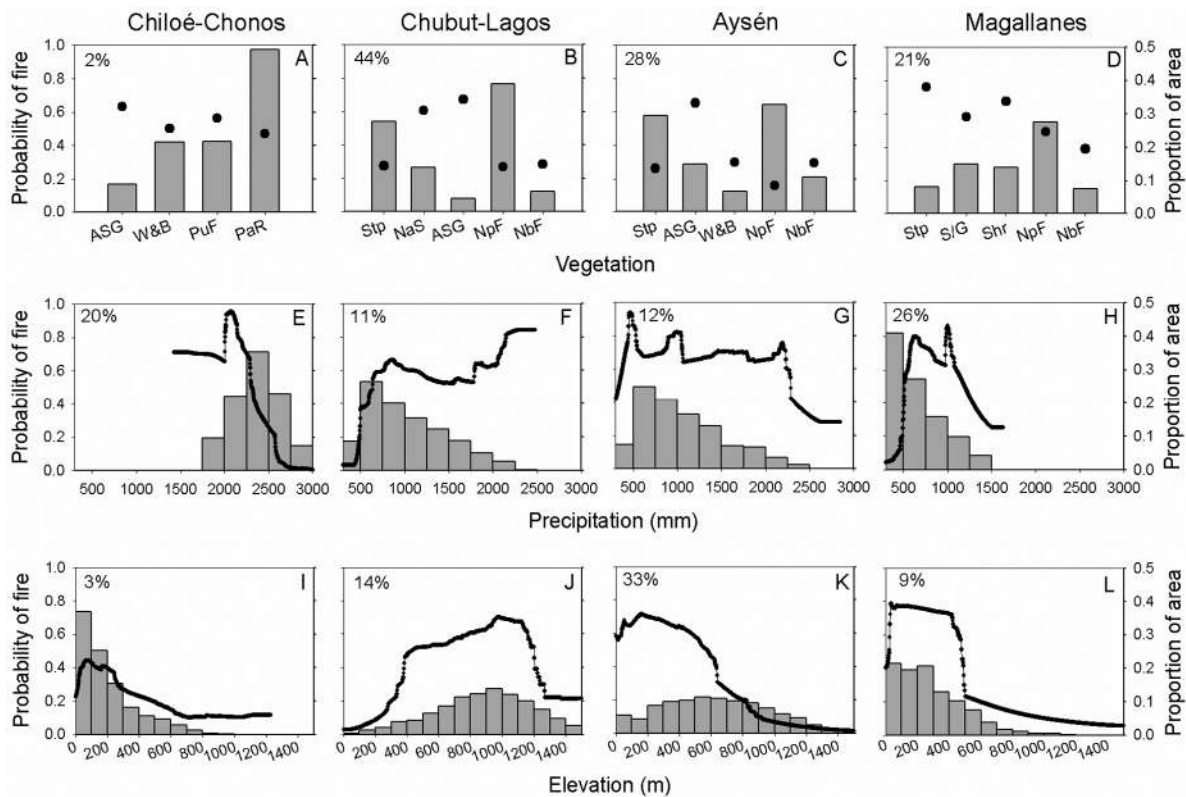


Fig. 4. Curves (and dots for categorical variables) indicating the influence of each biophysical variable on the MaxEnt prediction. Grey bars indicate the distribution of the proportion of area available to burn for each variable. The curves (and dots) show how the logistic prediction changes as each predictor varies, keeping all other environmental variables at their mean sample value. Percentage contribution of the predictor variable to the model for each study area is shown in the upper-left corner of each plot. Vegetation classes in A-D are as follows: ASG = Anthropogenic shrublands and grasslands; W&B = Wetlands and bogs; PuF = *Pilgerodendron uviferum* forests; PaR = Patagonian rainforests; Stp = Steppe; NaS = *Nothofagus antarctica* shrublands; NpF = *N. pumilio* forests; NbF = *N. betuloides* forests; S/G = Shrublands/grasslands; Shr = Shrublands.

*Nothofagus* spp. forest for the three study areas encompassing high proportions of xeric vegetation classes contrasts with the relatively uniform propensity to burn of vegetation classes in the CC study area characterized by hydric and mesic vegetation types (Fig. 4A).

In all four study areas, propensity to burn is low at the dry extreme of the precipitation gradient and rises sharply under less xeric conditions (Fig. 4E–H). In CC and MA, where precipitation contributed 20% and 26%, respectively, to the models, areas with intermediate precipitation levels exhibited higher probability of fire compared with areas at both extremes of the gradient (Fig. 4E and H). All four study areas exhibited reductions in probabilities of fire at

higher elevations (e.g., elevations greater than ca. 50th to 80th percentile). The three study areas that encompass more area of drier habitat to the east show similarly steep declines in fire probability towards high elevations (Fig. 4J–L). The decline initiates at a lower elevation in MA (Fig. 4L), the highest latitude study area where the upper elevation limit of vegetation is lower. For the uniformly mesic to wet study area CC there is relatively little variation in fire probability with elevation and in fact elevation only contributed 3% to the model of fire probability for this study area (Fig. 4I).

The relationship between probability of fire and distance to roads revealed two patterns. In CL, AY and MA the probability of fire is high in

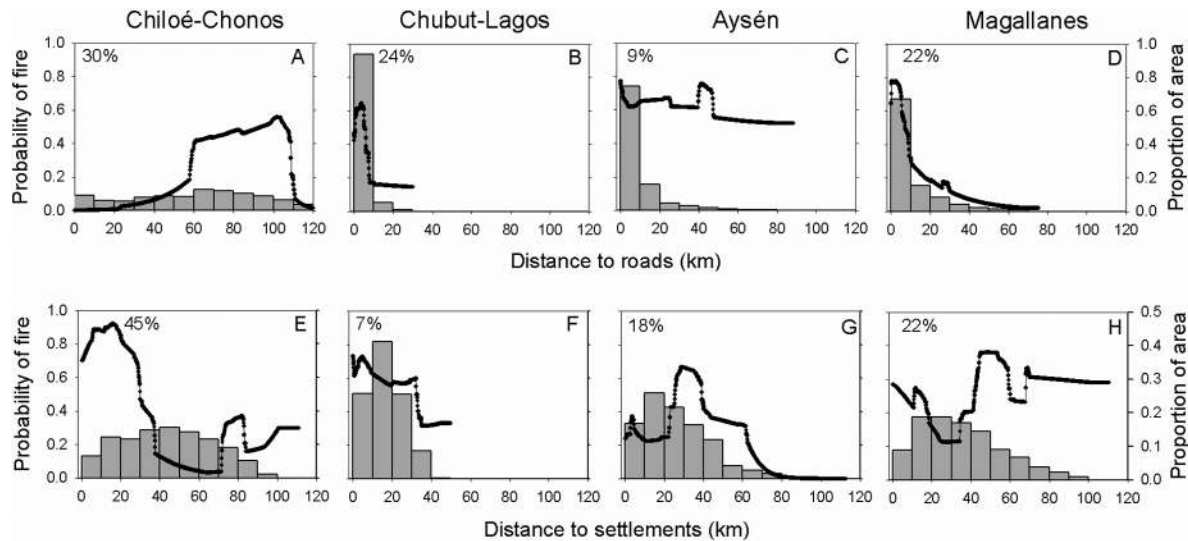


Fig. 5. Curves indicating the influence of each anthropogenic variable on the MaxEnt prediction. Grey bars indicate the distribution of the proportion of area available to burn for each variable. The curves show how the logistic prediction changes as each predictor varies, keeping all other environmental variables at their mean sample value. Percentage contribution of the predictor variable to the model for each study area is shown in the upper-left corner of each plot. Note the different scales in the right y-axes.

close proximity to roads and declines at distances  $>10$  km (Figs. 5B–D, 6B–D). In contrast, in CC, fire probability is minimal near roads and rises at distances greater than ca. 60 km from roads (Figs. 5A, 6A). Fire probability within 20 km of settlements reaches high values of ca. 0.6 to  $>0.9$  for study areas CC, CL and MA and of 0.4 for study area AY (Figs. 5E–H, 6A–D). AY and MA exhibit peaks of maximal fire probability at ca. 25 to 40 km and at 45 to 55 km from settlements, respectively (Figs. 5G–H, 6C–D).

## DISCUSSION

This is the first study in Patagonia that evaluates the spatial variability in fire activity in relation to potential biophysical and anthropogenic predictor variables over a broad scale  $\sim 1,200$  km north-south and 260 km west-east gradients. Vegetation class was a strong and consistent predictor of fire probability in regions where vegetation gradients extended from wet or mesic forests through xeric shrubland and grassland. In general, areas covered by vegetation with intermediate productivity levels, such as shrublands, have higher fire probability compared with areas of low (steppe) and high

(wet forests) productivity levels. Distance to roads and settlements were also strong predictors, suggesting that fire in all regions is ignition-limited. However, these anthropogenic predictors influenced probability of fire differently among study regions depending on their main land-use practices and their past and present socioeconomic situation. For instance, in the remote and virtually roadless archipelagos of CC fire probability increased with distance from roads whereas in the other regions, where roads are present, we documented the opposite trend.

There is a strong and consistent influence of vegetation class on probability of fire in all study areas that encompass the full gradient from wet or mesic forests to xeric shrublands and steppe. The exception to this pattern, CC, is characterized by uniformly mesic or hydric vegetation types, and here vegetation contributes only 2% to the model (Fig. 4A). In CL, AY and MA, shrublands and grasslands have higher probabilities of fire occurrence while tall forests of *Nothofagus pumilio* and *N. betuloides* have markedly lower fire probabilities compared to other vegetation types (Fig. 4B–D). Even in the case of wetlands and bogs, which occur extensively in the AY study area, the probability of fire is higher than in

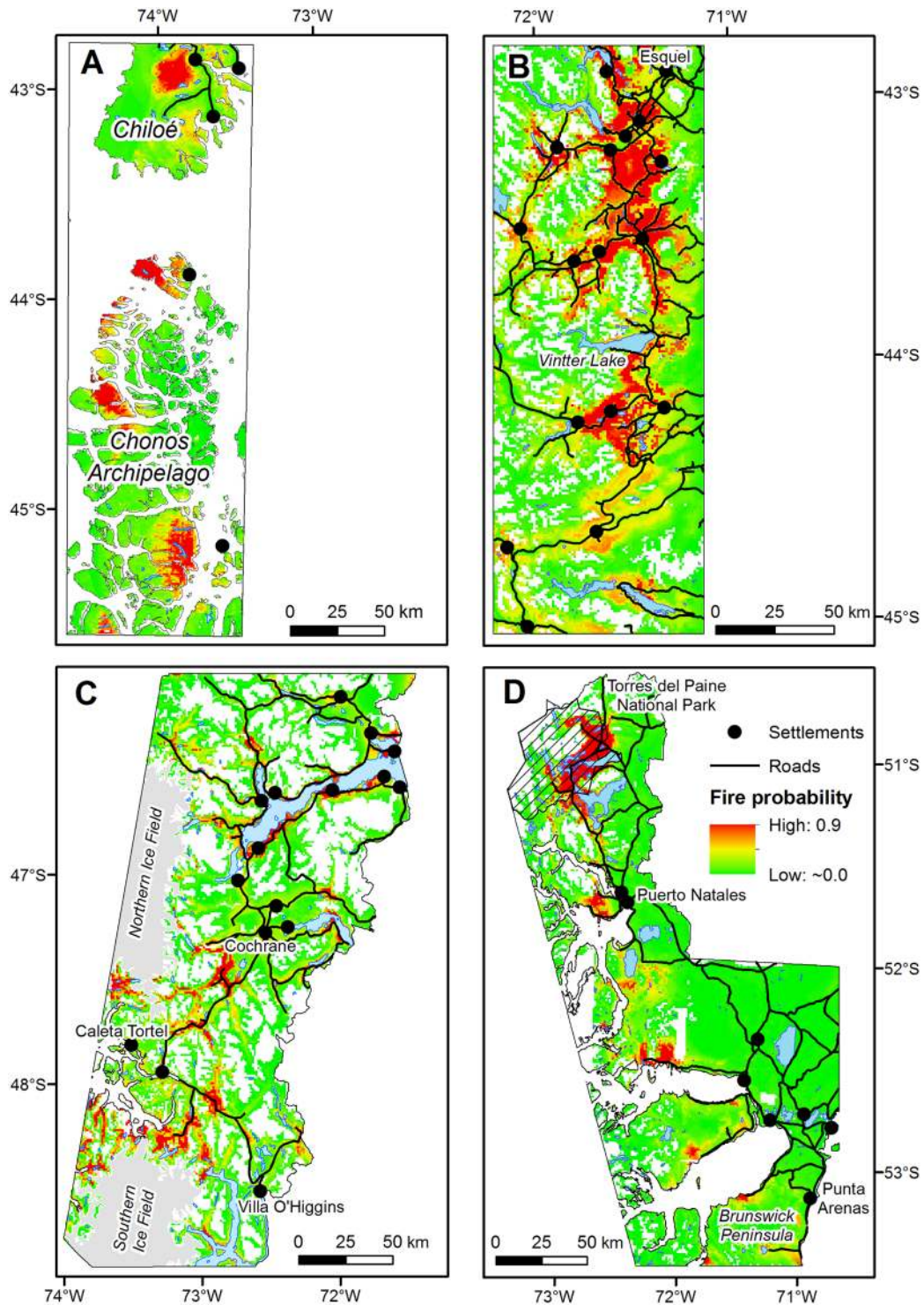


Fig. 6. Predicted fire probability for each study area based on fires that occurred over the 1984–2010 period. Locations of human settlements and road networks are also shown for each study area: (A) CC, (B) CL, (C) AY, and (D) MA. Legend in (D) applies to all panels.

tall *Nothofagus* forests (Fig. 4C). During summer droughts, the fine fuels of wetlands dry more quickly than the coarse fuels of tall forests. Indeed, wetlands in this region are targeted for intentional burning to facilitate extraction of the conifer *P. uviferum* because of greater ease of ignition (Holz and Veblen 2011a).

The contrast between relatively fire-resistant tall *Nothofagus* forests versus fire-prone shrublands documented in the current study extends the evidence for this pattern first documented in northern Patagonia (40° to 43° S) to a broader latitudinal range from ca. 43° to 53°30' S in southern Patagonia (Veblen et al. 2003, Mermoz et al. 2005). In northern Patagonia many of these post-fire shrublands are dominated by tall bamboos (*Chusquea culeou*) which provide abundant fine fuels that are easily desiccated and enhance the flammability of these shrublands (Veblen et al. 2003). Despite the scarcity of the bamboo south of 44°30' S in the CL study area and its complete absence south of 47° S (Parodi 1941) the pattern of fire-resistant *Nothofagus* forests and fire-prone tall shrublands persists throughout southern Patagonia. Higher flammability of shrublands is related to various factors. Among these are the high density of multi-stemmed woody species, the heavy loads of fuel ladders formed by flammable vines, such as *Mutisia* spp., the rapid accumulation of dry fine fuels from partial crown dieback of several woody species, and the dominance of plant species with higher foliar flammability (Veblen et al. 2008, Blackhall et al. 2012). Conversely, tall *Nothofagus* forests have single-stemmed tree species, coarser fuels, shady and moist understory microclimates, and lack ladder fuels between the understory and the tree canopy (Veblen et al. 2008).

Mean annual precipitation generally played an important role in the models. The peak probability of fire at intermediate precipitation levels observed in all study areas is consistent with biomass limitation to fire in the drier areas and the fuel desiccation limitation towards the moister end of the gradient (Pausas and Bradstock 2007, Krawchuk and Moritz 2011). The three study areas that include xeric ecosystem types (CL, AY, MA) exhibit sharply reduced probabilities of fire at the dry extremes where fuel continuity in the steppe vegetation is

limiting to fire spread (Kitzberger et al. 1997, Holz et al. 2012b). Towards the moist end of gradients, fire probability drops sharply in all study areas with the exception of CL; however, if we consider CC as a continuation of the precipitation gradient of CL it becomes clear that fire probability also drops at the moister extreme of this extended gradient (Fig. 4E–F). The sharp decline in fire probability in MA at precipitation values higher than 1,000 mm probably reflects greater effective moisture at the cooler temperatures of these high latitudes.

Higher elevations are associated with reduced fire probabilities in the three study areas most likely due to the increased dominance of pure subalpine forests of *N. pumilio* at higher elevations. Towards higher elevations this species develops into dense closed canopy subalpine forests resulting in cool moist understory conditions that are less conducive to fire (Mermoz et al. 2005). Although CL shows reduced fire probability at the lowest elevations, there is exceedingly little land area below 400 m in this study area. In AY and MA fire probability decreases with increasing elevation and maximal fire probabilities occur from sea level to ca. 500 m. It is difficult to separate the effects of elevation on this fire probability pattern from the contribution of more anthropogenic ignitions in low and mid-elevations that are more favorable for livestock raising and other land uses. In addition, valley bottom sites are more likely to be occupied by shrublands and grasslands which further enhance fire probability. The lack of significant contributions of slope angle and aspect to the models is most likely due to the coarse scale (1 × 1 km) of the analysis which often obscures such relationships (Cary et al. 2006).

Overall, there are strong influences of anthropogenic variables on probability of fire as indicated by the combined percentage contributions of distance to roads and settlements to the models that range from 27% (AY) to 75% (CC), suggesting that all areas are strongly ignition-limited. However, there are considerable differences in the spatial associations of fire probability with distances to roads and settlements (Fig. 6) that reflect important differences in land-use practices as well as time since initial colonization and permanent settlement among the study areas. The three inland study areas with better



developed road networks all show high fire probability in close proximity to roads (Figs. 5B–D, 6B–D). In contrast, for study area CC where roads are scarce and access is mostly by sea, no such relationship was found (Figs. 5A, 6A). Instead, fire locations are mostly in areas accessible from the sea (Fig. 2A). Roads in CC are scarce and restricted to Chiloé but nearly 75% of the area burned is distributed in the Chonos Archipelago, which has no significant road network (Fig. 2A). Roads are not a good indicator of anthropogenic disturbance at this study area, since most of the fires are ignited by humans reaching the islands by sea (Holz and Veblen 2011a).

Proximity to settlements is associated with higher fire probability in all four study areas (Fig. 5E–H) clearly demonstrating the importance of humans as a source of ignition. Again, the type of economic activities in a study area is reflected by spatial patterns of fire activity. For example, the second peak in fire probability at 45 to 55 km from settlements in MA clearly reflects the influence of two large fire events (1985 and 2005, ca. 15,000 ha each) in Torres del Paine National Park that account for most of the area burned in this region between 1984 and 2010. Torres del Paine National Park is roughly 55 km from the closest town (Puerto Natales). Virtually all the area burned within the park boundaries in the study period resulted from accidental fires set by park visitors, due to high rates of public visit (e.g., Vidal and Reif 2011). Thus, in this study area where the impact of humans is greatest in parks where settlements are minimal, roads rather than settlements are a better proxy of human activities in this region. In AY most fires are located in the southernmost area, which is a frontier zone where settlements and roads are incipient. Road construction is recent in Caleta Tortel (ca. 2003) and Villa O'Higgins (late 1990s), which are located in the AY study area (Fig. 2C). This illustrates the importance of a currently active frontier zone vs. a much older colonization in CL, which also has a more developed road network.

Previous studies conducted in northern Patagonia have shown that human presence plays a key role in increasing fire activity. In northern Patagonia, proximity to the WUI increased fire activity as a result of a higher rate of ignitions

(Mermoz et al. 2005). Reconstructions and analyses of fire regimes in relation with human presence through time in areas within the CC and AY study areas also show that humans have a significant role in amplifying fire activity (Holz and Veblen 2011a). Thus, despite occurrence of maximal fire probability distant from roads or human settlements in some regions, human presence seems to increase fire probability in western Patagonia regardless of socioeconomic factors and land-use, at least during the evaluated time periods and at the analyzed scales. Ethnographic studies in Patagonia have documented frequent intentionally-set fires that become wildfires due to poor fire management or that are deliberately set as wildfires to promote resource extraction, acquisition of land, or to express social tension (De Torres Curth et al. 2012, Marini 2012). The contrasts among regions for the anthropogenic variables show that differences in land-use activities, such as marine resources vs. livestock raising, have strong influences on the spatial associations of fire with roads and settlements. Also, differences in stage of development since initial colonization are important (e.g., southern AY vs. CL). Consequently, it is important to consider all these factors when interpreting the spatial associations of fire with anthropogenic variables which we are able to do given availability of information on histories of land use (e.g., Torrejón et al. 2004, Martinic 2005). However, a more certain explanation of these spatial associations requires in-depth understanding of human behaviors that in turn requires ethnographic analyses (e.g., Marini 2012).

## CONCLUSION

Recently developed models of fire probability at the global scale yield useful insights into the broad-scale biophysical drivers of fire activity (Chuvienco et al. 2008, Moritz et al. 2012). Comparison of contrasting ecosystems around the globe allow to identify limiting and promoting factors of fire activity (Moritz et al. 2012). However, efforts to model fire activity at a global scale are severely hampered by reliance on short time-series (<10 years) of fire activity obtained from satellite imagery and the coarse-resolution of data on human factors that affect fire activity.

For instance, fire data acquired from the Moderate Resolution Imaging Spectroradiometer and from Along-Track Scanning Radiometer begin only in 2000 and 1995, respectively. Thus, there is still much uncertainty about the role of humans as an influence on fire activity at a global scale (McWethy et al., *in press*), and in particular how human influences on fire regimes vary with both biophysical and socio-economic context. While biophysical data at fine resolution (e.g., 1 km<sup>2</sup>) is becoming increasingly available for much of the globe, high quality spatially explicit fire activity records spanning more than 20 years are largely limited to wealthy nations mostly located in the northern temperate zone. In the current study we overcame this data limitation by interpreting fire activity from satellite imagery for the period 1984 to 2010 in Patagonia to produce the first multi-decadal spatially explicit dataset on fire activity anywhere in South America.

In an Andean-Patagonia study area extending from ca. 42°50' to 53°30' S latitude and ranging from temperate rainforests to xeric woodlands and steppe, MaxEnt spatial modeling identified the biophysical and human “environmental space” of wildfire. Examination of fire patterns across broad gradients of biophysical gradients at fine-scale resolution (1 km<sup>2</sup>) revealed the relative roles of vegetation type, precipitation, and elevation as predictors of fire probability. By conducting analyses in four large regions of known current and past socioeconomic contexts, we were able to make coherent interpretations of spatial variables reflecting human impacts on fire activity. Our results emphasize the role of strong contrasts in the flammability of broad vegetation classes in determining fire activity at a regional scale, while also documenting the spatial influence of anthropogenic variables on fire activity in southwestern Patagonia.

In particular, the juxtaposition of fire-resistant tall forests with fire-prone shrublands and woodlands creates the potential for positive feedbacks from human-set fires to gradually increase the flammability of tall forests through repeated burning and conversion to more flammable vegetation types. We propose that research on fire activity combining both fine-scale resolution across broad biophysical gradients with relatively well understood socioeconomic contexts, such as the current one and others (e.g.,

Moreira et al. 2009), can provide important links to global approaches to understanding future trajectories in fire activity.

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