Chapter 4

Characterizing Predictability of Fire Occurrence in Tropical Forests and Grasslands: The Case of Puerto Rico

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Additional information is available at the end of the chapter

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Abstract

Global estimates of fire frequency indicate that over 70% of active fires occur in the tropics, and the size and frequency of fires are increasing every year. The majority of fires in the tropics are an unintended consequence of current land-use practices that promotes the establishment of grass and shrubland communities, which are more flammable and more adapted to fire than forests. In the Caribbean, wildland fires occur mainly in dry forests and in grasslands and crop lands. Climate change projections for the Caribbean indicate increasing area of drylands and subsequent increasing potential for wildland fire. We assessed the last decade of fire occurrence records for Puerto Rico to quantify the relative importance of time, climate, land cover, and population to inform predictive models of fire occurrence for projecting future scenarios of fire risk. Kruskal-Wallis, generalized linear models, robust regression, simple and multiple regressions, and tree models were used. We found that hour of the day (time), mean minimum temperature (climate), and percent forest cover (land cover) significantly influenced fire occurrence, while population showed a weak effect. Many variable interactions showed to be important. These significant variables and interactions should be considered in fire-predicting models for the island.

Keywords: wildfire, tropical dry forests, wildfire predictability, climate change, Caribbean

1. Introduction

Wildfire is an important natural process that shapes many terrestrial ecosystems because it influences species composition and community structure and function [1–5]. The occurrence and extent of wildfires are controlled by climate, operating at regional to global spatial scales and at interannual to multidecadal temporal scales [6–10]. Fire occurrence and spread is also controlled by local factors such as ignition source, topography, local weather patterns, variations in fuels type and condition, and management actions [6, 7, 9, 11–15]. Because of the complex interplay among drivers of wildfires, predicting fire occurrence in the context of global change is a challenge [16–18].

Predicting fire occurrence in the tropics and subtropics is especially urgent as vulnerabilities are expected to increase in the coming decades as changing climate influences temperature and precipitation patterns [19]. Current global estimates of fire frequency indicate that over 70% of active fires occur in the tropics [20] and that the size and frequency of fires are increasing every year [10, 21]. Among climate variables found to be determinant for fire occurrence in the tropics and subtropics, daily and monthly precipitation and daily relative humidity were negatively associated with fire ignitions [22, 23]. In addition to climatic drivers, fires in the tropics are unintended consequence of current land-use practices [21, 24–26] that promote the establishment of grass and shrubland communities, which are more flammable and more adapted to fire than evergreen forests [27–31]. In the Caribbean, although there is a general lack of available data on fire occurrence it appears that wildfires occur mainly in grasslands and crop lands [25], and in dry forests [32]. Lowland moist and montane forests are less susceptible to fires, though they can burn in dry years [25]. Understanding the relationship of current climate, landscape, and population can help predict the likelihood of increasing risk of fire occurrence in light of climate change projections in tropical islands [33]. Puerto Rico is an example from a tropical insular region where rapid and complex changes in land-use and land-cover (LULC) are occurring and where fire-prone ecosystems are being created [34, 35]. Puerto Rico land-use and land-cover changes in managed and unmanaged reforestation of abandoned agricultural lands, and deforestation and fragmentation related to population increases and urban development [36, 37] have created a complex, fragmented landscape of wildland-urban interface [38]. This has produced a shift in the fire regime from one of *fewer* natural fires prior to human habitation of the island, to possible use of fire in pre-Columbian times, through a pattern of widespread agricultural burning during the sugarcane era, to the current regime of thousands of small to intermediate scale human-induced fires occurring in a wildland-urban interface of forests and grasslands. In Puerto Rico, the limited available data related to fire occurrence suggest that most fires occur in dry areas of pasture, sugarcane, or abandoned lands in the southern part of the island [24]. In addition, historical information suggests that only 5% of the unintended wildfires in Puerto Rico in 1999 were caused by lightning and 95% were human-caused [24]. Present data and historical and paleoecological evidence suggest that fire frequency is increasing in the island and that fires are beginning to occur in areas of humid forests never known to have been burned [39]. Grassland and forest fires are common during the dry season but there is little information regarding the short- and long-term effects of fires. The cumulative effect of the current wildfire regime in Puerto Rico, over 5000 fires yearly, is unknown and it is expected that even slight climatic warming and drying areas have the potential to increase fire frequency and fire-related economic and ecological effects in the island.

In this study we analyzed field-collected data on fire occurrence in Puerto Rico between 2003 and 2011 to answer the questions: (1) How did fire occurrence vary in time (daily, seasonally, and yearly)? (2) How was fire occurrence related to decadal climate means (temperature and precipitation)? (3) What was the effect of land cover type on fire occurrence? and (4) What was the effect of population per *barrio* on fire occurrence? Our results will help to understand the conditions driving fire patterns and dynamics and hence inform predictive models of fire occurrence for projecting future scenarios of fire risk in the island.

2. Methods

2.1. Study area

The island of Puerto Rico is located in the northeastern Caribbean Sea, at ~17°45′N–18°30′N, and ~65°45′W–67°15′W. Its area is about 8740 km^2 and has a predominantly maritime climate, with orography strongly controlling local patterns and variation in decadal means of temperature and precipitation [40]. Early rainfall season occurs from May through June and a late rainfall season occurs from August to November. Puerto Rico is topographically diverse in terms of elevation and slope. Elevation ranges from sea level to 1338 m above the sea level in the central mountains. Therefore, climatic conditions across the island are highly variable. Six life zones have been described, ranging from subtropical dry forests to subtropical rain forests [41]. Dry, open forests are located in the south, and wetter, more closed forest are located in the north, east, and in the central mountains. The landscape is a complex matrix of wildlands, developed areas, and agricultural lands [42, 43].

2.2. Data acquisition

We used the information on fire occurrence collected by the Fire Department of Puerto Rico between 2003 and 2011. Information related to fire location was available for all the 78 municipalities of Puerto Rico. A total of 46,955 fires were reported by the Puerto Rico Fire Department occurring in this time period and we could assign the *barrio* (smallest administrative unit) information to 34,636 (74%) fires. Only this subset could be located at the *barrio* level because many fire locations were described using general information (e.g., route number but not km). Likewise, it was not possible to convert fire location descriptions into map points with unique latitude and longitude values. Fire location descriptions were used to determine the number of fires at the municipality and *barrio* levels. Around 832 of the 902 *barrios* were represented across the island (92%), capturing all the variability in climatic conditions (wet to dry environments), elevation (high to low elevation), and degree of urbanization (urban or rural areas). In addition, information about hour of occurrence was available for 1682 fires (~5%) occurring between 2008 and 2010.

Climate variables (daily temperature and precipitation) were obtained from the National Weather Service Cooperative Observer stations for the period 2002–2011 and interpolated across the island. Land cover classes were obtained from the Puerto Rico 2000 GAP Land Cover [43]. Population data were obtained from the US Census Bureau (2010 Census; [44]).

2.3. Data analysis

Fire occurrence was summarized across the island in relation to hour, month, and year of occurrence. A Kruskal-Wallis test was used to test for differences among hours, and ANOVA test were used to test for differences among months and among years. Generalized linear models (GLM) were used to identify the time variables and interactions that contributed most to fire occurrence at the *barrio* level.

To identify the climate variables that contributed most to fire occurrence we ran a robust linear model (robustbase package; [45]). Robust regression was used to account for non-normal measurement errors in the data, given their nature; this analysis provides a statistical framework from which to both identify and limit the influence of extreme values or leverage points on parameter estimation [46]. The number of fires per *barrio* was analyzed as the response variable and the climate variables mean daily maximum temperature, mean daily minimum temperature, mean daily annual precipitation, and interactions were analyzed as explanatory variables.

To determine the effects of land cover on the occurrence of wildfires we performed linear model selection using number of fires per *barrio* as the response variable and percent forest, percent woodland/shrubland, percent nonwoody vegetation (including grasses), percent urban, and percent forest edge per *barrio* as explanatory variables. A regression was run to account for the effect of population on the occurrence of wildfires (number of fires) at the *barrio* level.

Number of fires per *barrio* was log transformed and quadratic terms of the explanatory variables were added when necessary. Tree models were used in combination with linear models to examine the order of importance of the variables when necessary. All data analyses were performed using the *R* statistical package [47].

2.4. Results

Fires were registered and managed in the 91 fire stations located along the 78 municipalities on the island (**Figure 1**). On average, fire extent was 1.52 ha with a standard deviation of 4.67 (n = 2472). The number of fires per municipality ranged from 69 to 2174. The municipalities that registered more fire episodes between 2003 and 2011 were located mainly south of the island while municipalities with less number of fires reported were located north. The number of fires per 1000 persons was higher (40–56) in seven municipalities located south and west of the island (**Figure 1a**). The same spatial pattern was found in relation to municipality area, the highest numbers of fires per km^2 (10–17) were found in six municipalities located *mainly in the south* and *located in the north* west area of the island (**Figure 1b**). At the *barrio* level, the number of fires ranged up to 783. Most of the *barrios* with high number of fires were located in the south of the island (**Figure 1c**).

Most of the fires were reported during the afternoon (KW chi-squared = 653.08, df = 11, $p < 2.2e{-}16$: **Figure 2a**). Specifically, fire events increased significantly from around 15 fires per *barrio* at

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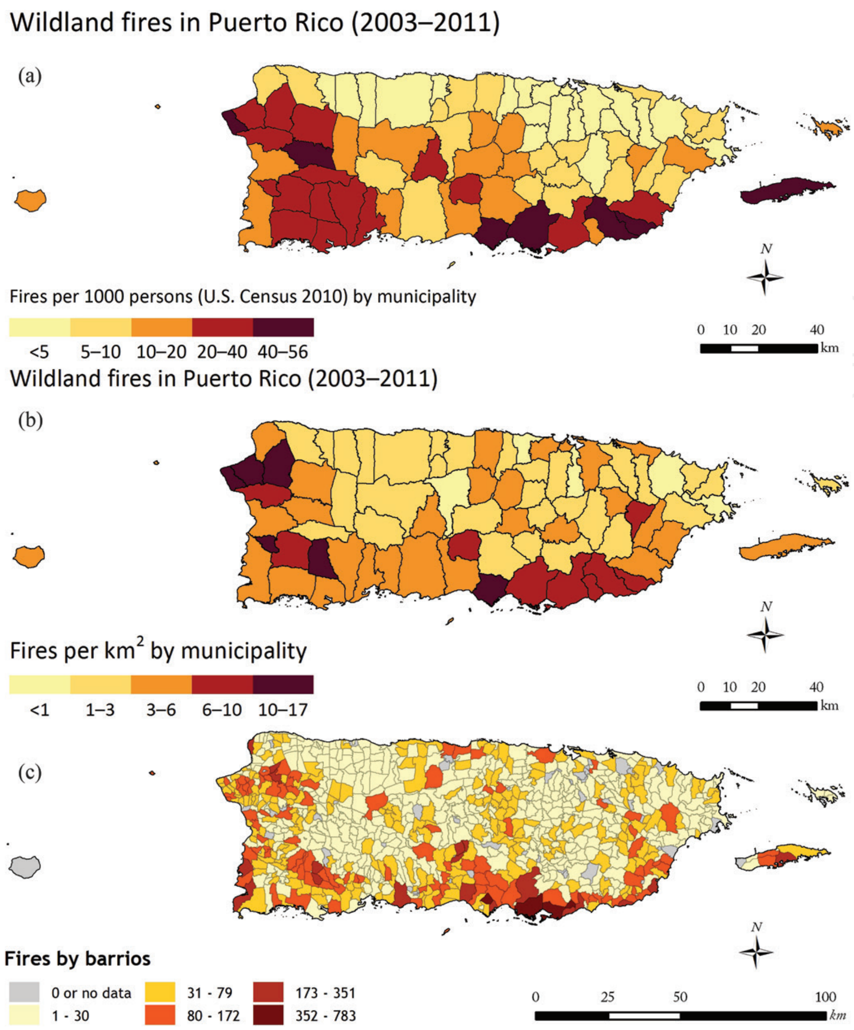

Figure 1. Maps of Puerto Rico showing the incidence of total number of fires (a) per 1000 persons by municipality, (b) per km^2 by municipality, and (c) per barrio where fire events were recorded from 2003 to 2011 by the Fire Department of Puerto Rico.

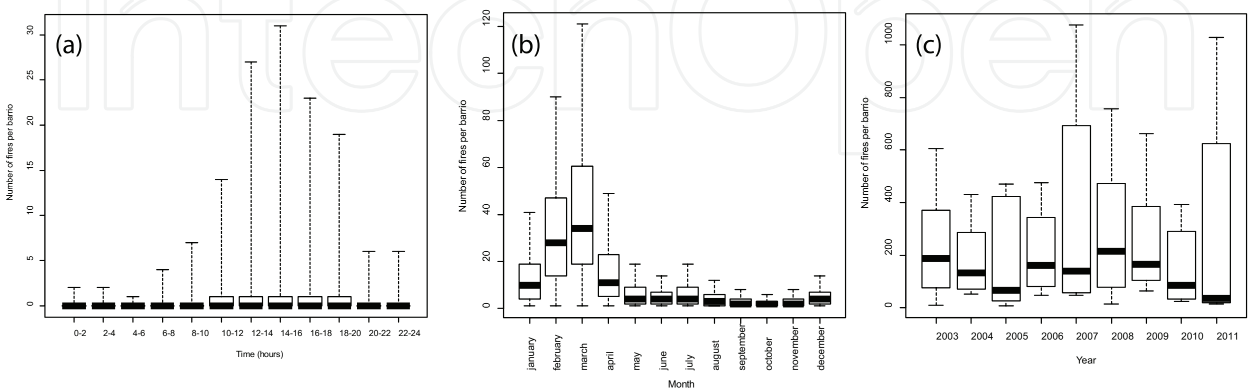

Figure 2. Box-and-whisker plots showing number of fires per barrio (a) throughout a day, (b) throughout a year, and (c) across years in Puerto Rico from 2003 to 2011. Each box shows the lower and upper quartiles, the black line within the box is the median, and the error bars are the minimum and maximum values, respectively.

10:00–12:00 hours ($n = 160$) to more than 30 fires at 14:00–16:00 hours ($n = 372$) and decreased to six fires at 20:00–22:00 hours ($n = 108$). Through the year, fires showed a peak between January and April ($F = 212.8$, df = 11, 2650, $p < 2.2e{-}16$; **Figure 2b**). Fire events increased from around 40 fires per *barrio* in January ($n = 3648$) to 120 fires in March ($n = 11674$) and then decreased to around 20 fires in May ($n = 1359$). In relation to year of occurrence, we found no significant differences among years from 2003 to 2011 ($F = 0.3663$, $df = 1$, 106, $p = 0.546$; **Figure 2c**). The GLMs combined with tree models showed that the interaction Hour*Month*Year was significant ($p = 2.466e{-}16$) and the order of importance of the three variables was Hour>Month>Year.

The number of fires per *barrio* was significantly influenced by all three climate variables, despite a high variability (Adj. R-squared = 0.062; **Table 1**, **Figure 3**). It was positively related to mean maximum daily temperature; the number of fires increased from 1 at 25°C to 783 at 30.7°C (**Figure 3a**). The number of fires per *barrio* was positively related to mean minimum daily temperature; it ranged from 1 at 16.2°C to 783 at 22.1°C (**Figure 3b**). The number of fires was negatively related to mean daily annual precipitation (**Figure 3c**); it decreased from 783 fires at 3.81 inches to 19 at 13.01 inches. All interactions performed in the robust regression were significant except for mean maximum daily temperature × Precipitation, which was marginally significant. The most significant relationship between number of fires per *barrio* and climate was mean minimum daily temperature (**Table 1**).

	Estimate	Std. error	t value	Pr(>|t|)
(Intercept)	135.79586	66.69509	2.036	0.0421*
Max.temp	−4.21917	2.23246	−1.890	0.0591.
Min.temp	−7.58724	3.39628	− 2.234	0.0258*
Precipitation	−19.46869	9.91169	−1.964	0.0498*
Max.temp: Min.temp	0.24307	0.11324	2.147	0.0321*
Max.temp: Precipitation	0.62015	0.33509	1.851	0.0646.
Min.temp: Precipitation	1.07691	0.50422	2.136	0.0330*
Max.temp: Min.temp: Precipitation	−0.03451	0.01697	− 2.034	0.0423*

Note: Max.temp: mean daily maximum temperature, Min.temp: mean daily minimum temperature, Precipitation: mean daily annual precipitation. Significance codes: 0.01 '*'; 0.05 '.'.

Table 1. Coefficients of the robust linear model using log(number of fires per *barrio*) as the response variable and climate variables as explanatory.

The best linear model explaining the effects of land cover on the occurrence of wildfires included simple terms, quadratic terms such as percent forest cover ^2, percent woodland and shrubland ^2, and percent nonwoody vegetation ^2, percent forest edge, and complex interactions (e.g., one five-term interaction) (Adj. R-squared = 0.2492, $F = 411.2$, $df = 28$, 34582, $p < 2.2e{-}16$; **Table 2**). According to the tree model, percent forest cover was the main variable explaining the number of fires per *barrio*, followed by nonwoody

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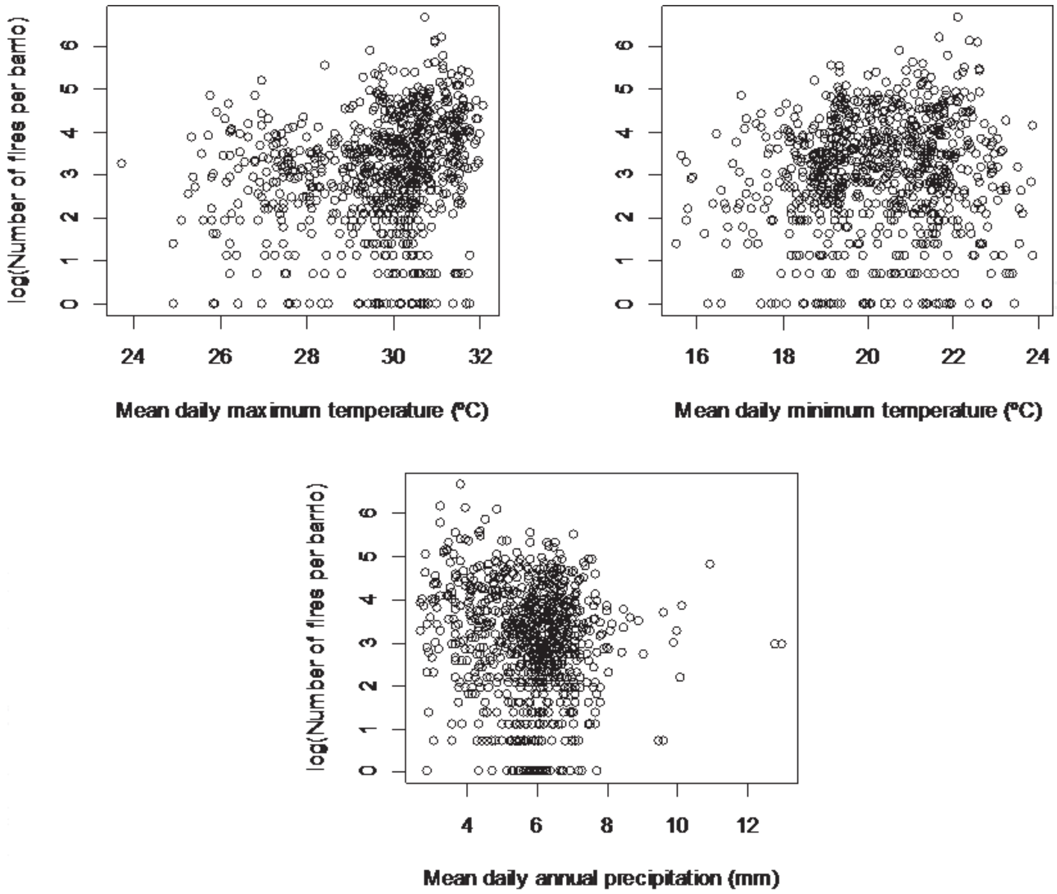

Figure 3. Scatterplots between the log(number of fires per barrio) and (a) mean daily maximum temperature, (b) mean daily minimum temperature, and (c) mean daily annual precipitation (see **Table 1** for coefficients).

Variable	Estimate	Std. error	t value	Pr(>|t|)
(Intercept)	3.009e+00	1.045e−01	28.810	<2e−16 ***
Forest	−1.589e−01	8.097e−03	−19.623	<2e−16 ***
Forest ^2	1.818e−03	7.659e−05	23.739	<2e−16 ***
Woodland and shrubland	2.430e−01	9.187e−03	26.455	<2e−16 ***
Woodland and shrubland ^2	−2.562e−03	9.672e−05	−26.494	<2e−16 ***
Non woody vegetation	8.168e−02	3.582e−03	22.803	<2e−16 ***
Non woody vegetation ^2	−5.936e−04	2.938e−05	−20.203	<2e−16 ***
Urban	9.217e−03	1.386e−03	6.650	2.97e−11 ***
Forest edge	1.391e+00	4.885e−02	28.483	<2e−16 ***
Forest: woodland and shrubland	−1.539e-03	1.145e−04	−13.435	<2e−16 ***
Forest: urban	1.786e−03	1.175e−04	15.202	<2e−16 ***

Variable	Estimate	Std. error	t value	Pr(>|t|)
Woodland and shrubland: urban	−1.725e−03	1.357e−04	−12.716	<2e−16 ***
Forest: non woody vegetation	7.496e−04	9.012e−05	8.318	<2e−16 ***
Woodland and shrubland: non woody vegetation	−2.633e−03	9.981e−05	−26.384	<2e−16 ***
Non woody vegetation: urban	−3.342e−04	5.014e−05	−6.666	2.66e−11 ***
Forest: forest edge	−1.519e−02	5.029e−04	−30.214	<2e−16 ***
Woodland and shrubland: forest edge	−2.205e−02	1.576e−03	−13.987	<2e−16 ***
Urban: forest edge	−2.413e−02	9.938e−04	−24.277	<2e−16 ***
Non woody vegetation: forest edge	−1.504e−02	6.052e−04	−24.843	<2e−16 ***
Forest: non woody vegetation: urban	−4.930e−05	3.473e−06	−14.195	<2e−16 ***
Woodland and shrubland: non woody vegetation: urban	−4.209e−05	4.967e−06	−8.473	<2e−16 ***
Forest: woodland and shrubland: forest edge	1.750e−04	1.880e−05	9.313	<2e−16 ***
Forest: urban: forest edge	2.064e−04	1.356e−05	15.225	<2e−16 ***
Woodland and shrubland: urban: forest edge	5.486e−04	6.695e−05	8.194	2.62e−16 ***
Forest: non woody vegetation: forest edge	1.467e−05	4.783e−06	3.066	0.00217 **
Woodland and shrubland: non woody vegetation: forest edge	1.704e−04	2.811e−05	6.061	1.37e−09 ***
Forest: woodland and shrubland: non woody vegetation: urban	5.076e−06	2.118e−07	23.973	<2e−16 ***
Forest: non woody vegetation: urban: forest edge	7.151e−06	1.059e−06	6.755	1.45e−11 ***
Forest: woodland and shrubland: non woody vegetation: urban: forest edge	7.991e−07	8.238e−08	−9.701	<2e−16 ***

Note: (Adj. R-squared = 0.2492, $p < 2.2e{-}16$). Significance codes: 0 '***', 0.001 '**'.

Table 2. Coefficients of the best linear model using log(number of fires per *barrio*) as response variable and percent land covers and percent forest edge as explanatory variables.

vegetation cover and urban cover. The log(number of fires) was negatively related to percent forest cover (**Figure 4a**). The number of fires decreased from 400–783 at 1–7% forest to 1–5 at 0–91% forest. The log(number of fires) was slightly positively related to percent urban cover (**Figure 4b**). Fires increased from 1–5 at 0–7% urban cover to 400–783 at 8–64% urban cover. The log(number of fires) was positively related to percent nonwoody vegetation cover (**Figure 4c**); fires increased from 1–10 at 0–78% cover to 436–783 at 28–84% cover. Lastly, the log(number of fires) was slightly negatively related to woodland and shrubland cover (**Figure 4d**). The number of fires decreased from 783 at 3% woodland-shrubland cover to 1 at 55% cover. A high variability was observed in the data in all cases.

The log(number of fires) was positive but weakly related to population (Adj. R-squared = 0.038, $p = < 2.2e\text{-}16$; **Figure 5**). The greatest incidence of fire occurred in *barrios* of intermediate population density.

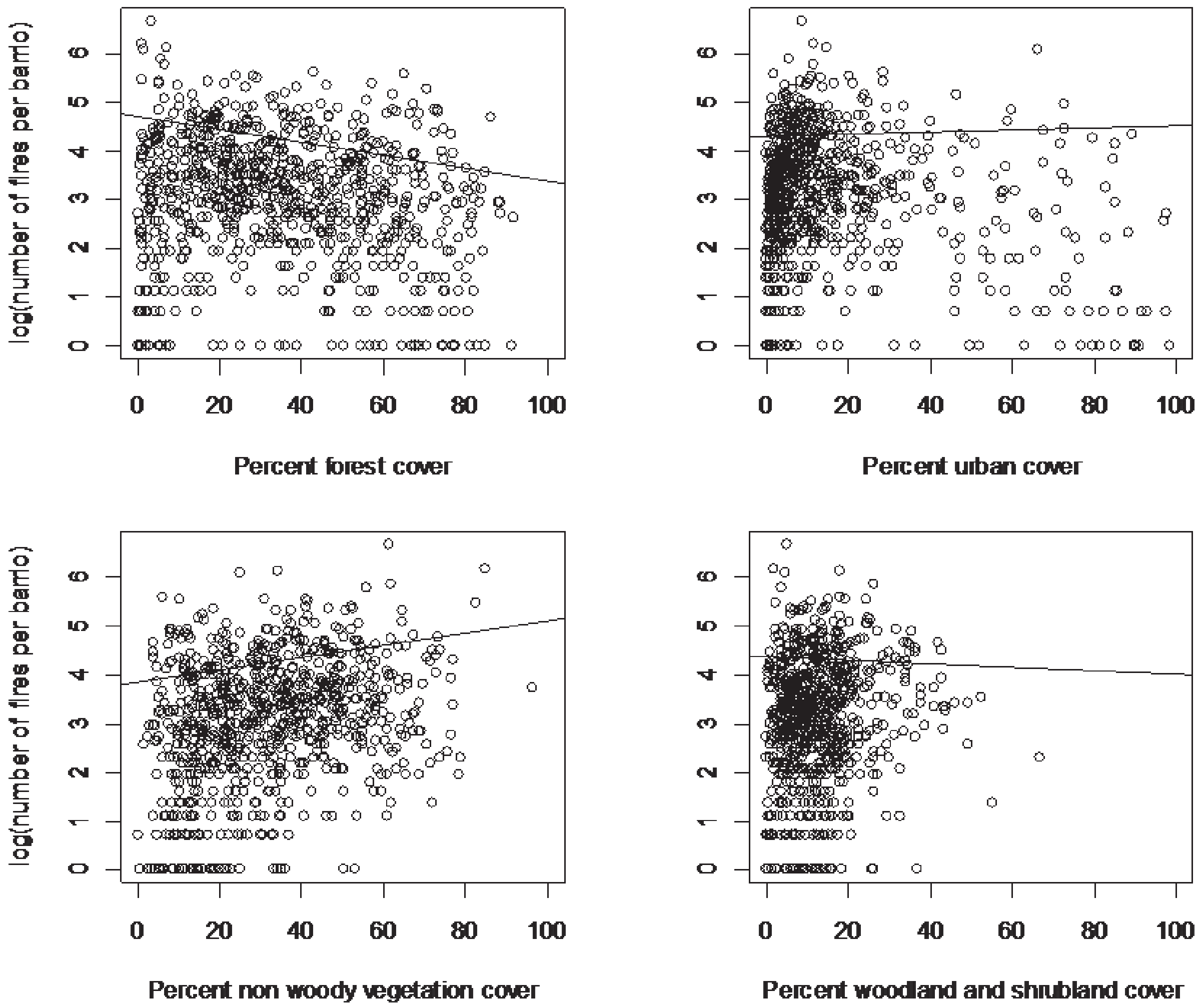

Figure 4. Scatterplots between the log(number of fires per barrio) and (a) percent forest cover, (b) percent urban cover, (c) percent non-woody vegetation cover, and (d) percent woodland and shrubland cover (see **Table 2** for coefficients).

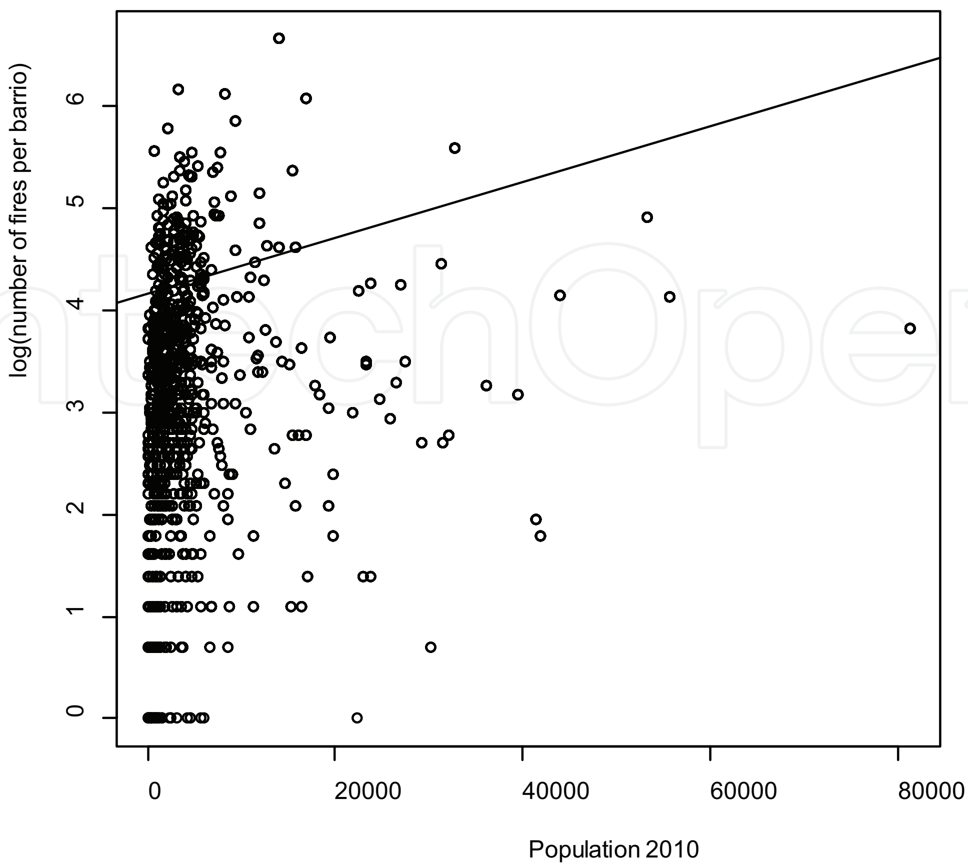

Figure 5. Scatterplot between the log(number of fires per barrio) and population according to the 2010 U.S. Census.

2.5. Discussion

We analyzed a total of 34,636 fires, most of them of small extent, reported by the Puerto Rico Fire Department from 2003 to 2011 for the entire island. Hour of the day (time), mean minimum temperature (climate) and percent forest cover (land cover) were found to significantly influence fire occurrence, while population showed a weak effect. In addition, many variable interactions showed to be important. These significant variables and interactions can be useful if considered in fire occurrence models for assessing fire risk under potential future conditions.

Our data support the idea that active fires occur in the tropics [25]. More fires were recorded at the municipalities in the southern, drier areas of the island than in the northern, more humid areas. Lowland moist and montane forests are less susceptible to fires than dry forests, but it was remarkable that in our study fires occurred in high frequency in many northern and central forests. These results support the idea that fires are beginning to occur in areas of humid forests never known to have been burned [39] and may be an indirect evidence of an increasing fire frequency through time, as suggested [21]. Alternatively, this may be a result of recording fires only recently in Puerto Rico, in contrast to temperate regions.

Time of the day was the most important determinant of fire occurrence among the time variables. It has been shown that "typical" fire weather conditions observed during the day can be abruptly worsened and fire risk increased when rapid increase in wind speed, decrease in

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relative humidity or both take place [48, 49]. This pattern is apparently independent of daily temperature thus we suggest to consider local conditions of wind and humidity in predicting models for Puerto Rico. Not surprisingly, fire occurrence was markedly seasonal and corresponded to the driest period of the year (January–April). Our results, though, did not show direct evidence of an increase in fire frequency through years, as suggested for other regions of the globe [21]. This result could change if the time frame for analysis is extended; alternatively, fire extent and/or intensity could be increasing over time but these aspects of fire were not evaluated in this study. The climatic variables mean daily maximum temperature, mean daily minimum temperature, and mean daily annual precipitation, averaged over the period 2003–2011, were significantly correlated with wildfire occurrence in Puerto Rico. In contrast to other tropical and subtropical countries [22, 23], mean annual precipitation was not the most important single influencing factor for fire occurrence. Instead, mean daily minimum temperature and daily thermal amplitude represented by the interaction between temperature maximum and minimum were more determinant for fire occurrence and of special consideration in predicting models. In another study using random forests and aggregating data into different day intervals we found that precipitation in fact explained fire occurrence better than temperature variables suggesting that precipitation variability rather than mean precipitation is a better predictor of fire occurrence in Puerto Rico [49]. In both cases, mean daily minimum temperature was more important than maximum temperature to explain fires. Given the projections that precipitation will decline in tropical islands including Puerto Rico and that this decline will cause increases in drought intensity [33], special care should be taken when selecting climatic variables for fire prediction models.

Land cover and forest edge were determinant for fire occurrence and the variability explained by the model was higher than that explained by climatic variables and population. This result contrasts with other studies that found stronger influences of climate than LULC on fire occurrence when using remote sensors [17, 22, 50]. An open question remains how different resolution fire data are explained by variables operating at different scales. Percent forest cover, negatively related to fire occurrence, was the main variable in our study explaining the number of fires per *barrio*, followed by nonwoody vegetation cover and to a lesser degree, urban cover, both positively related to fire occurrence. The negative relationship between percent forest and fire occurrence confirms patterns observed in other tropical regions [22]. From a subset of the Fire Department data we could determine that grass (GR4 and GR3 fuel models) was the dominant fuel type in Puerto Rico, followed by forest (TU and TL fuel models) (results not shown). Previous studies have shown that this is a general pattern in which fires occur mainly in dry forests, the most threatened tropical forest type [24, 32], and in grasslands and crop lands [25]. Grass and shrubland communities alter the vegetation cover [27–29] creating new fire-prone ecosystems and the land cover change favoring the establishment of grass would increase fire risk in Puerto Rico, as previously suggested [34, 35]. At the same time, the large percentage of wildland-urban interface (WUI) in Puerto Rico (36%) [38] could be promoting the occurrence of thousands of small to intermediate (<4 ha) scale human-induced fires as a result of closer interactions between humans, infrastructure, and natural lands. In this regard, in Puerto Rico and regions with similar climate and landscape mosaic characteristics, fire occurrence models may improve when they include climatic and LULC variables as both are significantly correlated with occurrence. Furthermore, integrating LULC variables in fire occurrence predictability is crucial in changing landscapes. In Puerto Rico, agriculture is slowly becoming an emergent economy in the island. Land use-land cover changes are expected to occur and the degree of land change would have a direct effect on fuel loads and hence on fire occurrence.

Population had the weakest effect on fire occurrence among the variables examined. A subset of the Fire Department data showed that for most of the fires reported in Puerto Rico between 2008 and 2010, the cause of ignition was unknown (results not shown). Given that historical information suggests that only 5% of the unintended wildland fires in Puerto Rico in 1999 were caused by lightning and 95% were human-caused [24], we conclude that those fires were the source of ignition was unknown were human caused. Given that nearly all fires are human caused, the action of people in combination with climate and LULC likely determines the ignition, spread and extent of fires in the island. The scenarios of population density and land use are changing throughout the tropics in complex ways, for example over the last decade in Puerto Rico, population has decreased while housing units have increased [51]. Thus, changes in fire occurrence increase may not be a consequence of population density per se, but can be responding to changing land use. Weak effects of population on fire occurrence have been reported in other regions of the world where humans influence variables were most strongly associated with fire size [50].

Additional factors not considered in this study could be added to predictive models in order to improve accuracy. In previous studies conducted in tropical and nontropical environments road density was determinant for fire occurrence [22, 52]. Roads increase the WUI, facilitating human access to shrubland, grassland and forest areas, increasing the probabilities of fire episodes. Furthermore, roads alter soil, microclimatic conditions and native vegetation [53] creating a fire prone environment. Puerto Rico is one of the countries with highest road density in the Caribbean [54] and including this variable in future models would provide a better understanding of fire occurrence based on climate and land local conditions.

Finally, we think that fire model accuracy can be improved by standardizing field data collection among fire managers and improving data acquisition such as recording exact fire location (i.e. latitude and longitude). This would increase data resolution and therefore models' accuracy. Furthermore, as it has been suggested that Random Forest models are better than Multiple Linear Regressions at predicting fire occurrence in some regions of the world [52], we recommend that different methods be implemented to compare their performance in tropical islands where the nature of data may be different.

2.6. Wildfires' effects on forest ecosystems and conservation

The occurrence of fires either in fire-adapted ecosystems (i.e., fire is a natural disturbance) or in non-fire-adapted ecosystems (i.e., fire is not a natural disturbance) produces changes in vegetation composition and structure, alters fuel loads and biomass, and shapes the landscape [3, 5, 6]. These changes are favorable in wildfire-prone ecosystems where fires are key in preserving ecosystem processes and promoting ecosystem resilience, while they can have adverse implications in ecosystems where fires do not occur naturally (e.g., [10]).

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In temperate forests where fire is a natural disturbance native species show different adaptations or life-history strategies such as resprouting from below-ground despite top-kill, preventing top-kill through fire resistance by the increase of bark thickness, among others [55]. In these forests with fire history succession paths depend strongly on fire events and infrequent severe weather conditions can lead to the burning of relatively fire-resistant forests with consequent expansion of shrublands at the expense of forests [12]. The result of these processes is an increase in anthropogenic ignitions and a conversion from forest to shrubland. In Puerto Rico, fire is not a natural disturbance in modern times. Most of the native plant species in Puerto Rico dry forests have a bark structure that unlikely prevents top-kill in even low-intensity fires [55], and hence are not well-adapted to fire episodes. Therefore, even a single low-intensity fire has the potential to kill most of the trees [55] and to change the structure and composition of the forest. In this regard, fires have a negative effect on forest restoration success and this is critical for the conservation of unique forest ecosystems such as the dry forest. In dry forests, a single fire episode can eliminate years of forest regeneration [56]. In addition, secondary forests in Puerto Rico are characterized by the presence of a variety of exotic species. In southern dry forests of Puerto Rico, exotic species such as *Leucaena leucocephala* are fire-adapted, spread easily after fire episodes and can establish into previously forested areas. These exotic fire-adapted species can dominate the canopy forest and maintain a fire regime, preventing the establishment of native trees and shrubs [57].

Fire management policies in temperate, fire-adapted forests should be different from policies applied in tropical and subtropical forests with no fire history. Common management practices in fire-adapted forests include to schedule and conduct fire ignitions under a highly controlled regime and to use wildland fires (i.e., allow natural fires to burn). These practices are used to remove excess fuel and to stimulate native plant growth and regeneration. In contrast, in Puerto Rico this kind of fire management practices are scarce. The only example is in Guánica Forest where prescribed fires have been used since 1986 in grass-invaded areas along roadsides during the beginning of the dry season to reduce grass fuels and to limit the occurrence of uncontrolled fires into adjacent forest [57, 58]. In this regard, in Puerto Rico and other tropical forests the conservation of native forests will be successfully achieved if fires are not prescribed but suppressed and avoided. Effective fire suppression will be achieved by speeding the fire-fighter response especially between 14:00 and 16:00 and by improving personal training. Based on our results, special attention should be given to days when minimum temperatures are extremely high and to regions of the island where forest cover is low. In addition, our data showed a high incidence of human-caused fires in different regions of the island, especially in dry forests where species are not fire-adapted. Due to the fact that most of forest fires are human caused, and given the large extent of WUI in Puerto Rico, education and awareness about fires in high sensitive areas is an important strategy that is being implemented.

2.7. Conclusions

Including hour of the day, mean minimum temperature, and percent forest cover in models predicting fire occurrence will likely improve accuracy for fire management in Puerto Rico. Surprisingly, including population does not show a strong effect on fire occurrence but a question remains open about its effect on fire size. These results are particularly relevant to design fire management practices that lead to successful forest conservation.

Our results were based on one of the largest fire datasets in the Caribbean and other tropical regions. The variables analyzed in our study have been explored in other tropical environments and some differences have been found, especially in relation to the relative importance of climate vs. LULC variables. Predicting fire occurrence in a context of global change is a challenge; care should be taken when analyzing individual tropical islands especially when taking variables' interactions into account. A deep understanding of socioecological interactions in each case is necessary to incorporate relevant variables into fire predictive models and understand model's output to correctly translate them into management actions. We anticipate that standardizing field data collection and comparing different statistical methods in tropical islands will improve our understanding of fire occurrence in these environments.

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