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Interactions between Climate, Land Use and Vegetation Fire Occurrences in El Salvador

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Abstract: Vegetation burning is a global environmental threat that results in local ecological, economic and social impacts but also has large-scale implications for global change. The burning is usually a result of interacting factors such as climate, land use and vegetation type. Despite its importance as a factor shaping ecological, economic and social processes, countries highly vulnerable to climate change in Central America, such as El Salvador, lack an assessment of this complex relationship. In this study we rely on remotely sensed measures of the Normalized Vegetation Difference Index (NDVI) and thermal anomaly detections by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to identify vegetation cover changes and fire occurrences. We also use land use data and rainfall observations derived from the Tropical Rainfall Measuring Mission (TRMM) data to determine the spatial and temporal variability and interactions of these factors. Our results indicate a highly marked seasonality of fire occurrence linked to the climatic variability with a peak of fire occurrences in 2004 and 2013. Low vegetation indices occurred in March–April, around two months after the driest period of the year (December–February), corresponding to months with high detection of fires. Spatially, 65.6% of the fires were recurrent and clustered in agriculture/cropland areas and within 1 km of roads (70%) and only a 4.7% of fires detected were associated with forests. Remaining forests in El Salvador deserve more attention due to underestimated consequences of forest fires. The identification of these clear patterns can be used as a baseline to better shape management of fire regimes and support decision making in this country. Recommendations resulting from this work include focusing on fire risk models and agriculture fires and long-term ecological and economic consequences of those. Furthermore, El Salvador will need to include agricultural fires in the contribution to national accounts emissions.

Keywords: spatial pattern; temporal; satellite active fires; MODIS; NDVI; rainfall

1. Introduction

Fire is one of the evolutionary forces related to the modeling and evolution of terrestrial ecosystems, due to their impact on different processes and functions, as well as on the composition and structure of these ecosystems [1] Fires impact local and regional ecological processes, and have global impacts via influences on vegetation patterns and greenhouse gas emission budgets [2,3]. Climate modeling indicates that extreme fire weather conditions will occur for many tropical regions [4], and that increases in carbon emissions are expected [5]. Liu *et al.* [6] investigated the trend in global wildfire potential under climate change due to greenhouse gas effects. Increased fire potential is mainly caused by the combination of warming and drying in many regions, including the Americas. Their results suggest a dramatic increase in wildfire. The relationship between plant cover and fire has existed throughout history, and suggests that fire has a specific effect on biota [7]; however, there still remains an insufficient understanding of the role fires play in modulating vegetation cover, ecosystem dynamics, and global contributions to climate change.

Currently, the dynamics of fires in vegetation cover in the world are accompanied by anthropogenic regimes [8]. Fire has been extensively used for active landscape management, particularly with regards to clearing for agriculture [7]. Examples of this are found in tropical areas and in the subtropics where most vegetation related fires are started by humans [9] and used for a variety of purposes, but most often as a management tool for clearing forested and wooded areas for crops or grazing areas [10] or to eliminate agricultural waste [11]. Anthropogenic burning currently poses a threat to biodiversity and the conservation of natural areas [7,12]. Increases in fire occurrence from agricultural practices and deforestation are a major factor in climate change [13] contributing to increased anthropogenic emissions of CO_2 in the atmosphere [7].

The environmental problems accompanying the use of fire for the management of vegetation cover results in climate-vegetation-fire dynamics becoming a priority of interest, and a central focus to understanding the dynamics of this type of disturbance. The interactions between these three components are still unclear. However, it is known that weather is a global factor that directly influences the distribution of vegetation and in turn the characteristics of the fire regime [9]. Aragão *et al.* [14] show how the dynamics of fires are seasonal and directly related to climatic cycles, as the peak occurrence of fires in vegetation cover is consistent with the dry season in tropical ecosystems. Indeed, a lot of attention has been given recently to the increased frequency and severity of fires in the tropics with a focus on fires in the Amazon area [12,14–17] but less is known about fire dynamics in Central America [18], especially in countries other than Mexico [19]. As fire is a phenomenon both related to and influenced by climate cycles, the dynamics of fire regimes become important for regions like Central America. Of all regions in the Americas, Central America is probably one of the most vulnerable to climate change, as the mid-summer drought (or canicula) is projected to become even drier and hotter (e.g., [20]).

One of the Central American countries where fire has hardly been studied is El Salvador. It is estimated that during 2004, El Salvador's contribution to the total area burnt in Latin America was only 50 km^2 out of a total of 153,215 km^2 reported burnt areas across the entire region [18]. El Salvador is a good case study for the region because it has very high variation in land use, land cover, and topography across a relatively small area [21], as well as different climates, and rainfall distributions, from tropical savannah (Aw) to subtropical highland oceanic climate (Cwb), according to Koeppen. El Salvador's high rate of deforestation has resulted in the country retaining only 2% to 5% of its forests, giving the impression of a completely anthropogenic landscape [22,23]. Environmental policy, international migration, and civil war are related to the recovery of forest cover [24], thus redefining the idea of forest cover at the national scale. Recent studies report a forest cover of 23% [25]. Shifts in forest patterns at the national scale paralleled with changes in land ownership and use resulting from the negotiated Peace Accords [24] make El Salvador a useful case study site for an examination of the relationship between climate-vegetation-land use-fire dynamics. This study aims to characterize the spatial and temporal patterns of vegetation and fires in El Salvador in relation to land use and climatic variability. Specific study objectives include: (1) map spatial and temporal patterns of fires in El Salvador; (2) evaluate to what extent those patterns can be explained by vegetation and climatic variation; and (3) analyze the influence of anthropogenic drivers (land use) on fire patterns. The research relies on remotely sensed measures of vegetation cover and hot spots detection by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor to identify fire occurrences, and will provide a basic understanding of recent and current vegetation and fire patterns at a national scale.

2. Study Area

El Salvador is located on the south side of the Central America isthmus (13° to 15°N, 87 and 88° to 90°W). It has a southern coastline along the North Pacific Ocean and shares borders with Guatemala to the northwest and Honduras to the northeast. With an area of about 21,040 km^2, the country is considered the smallest country in the Americas. Two parallel mountain ranges extend over El Salvador in a WNW–ESE direction separated by a central plateau and rimmed by a narrow coastal plain next to the Pacific coast (Figure 1). The southern mountain range is actually a discontinuous chain of more than twenty Late Pleistocene to recent volcanoes clustered into six groups with attached remnants of older volcanic formations to the south, called the Cordillera del Bálsamo [26]. The chain of recent volcanoes follows the Central Graben and between the volcanic cones alluvial basins and rolling hills extend, eroded from ash/tuff deposits [26].

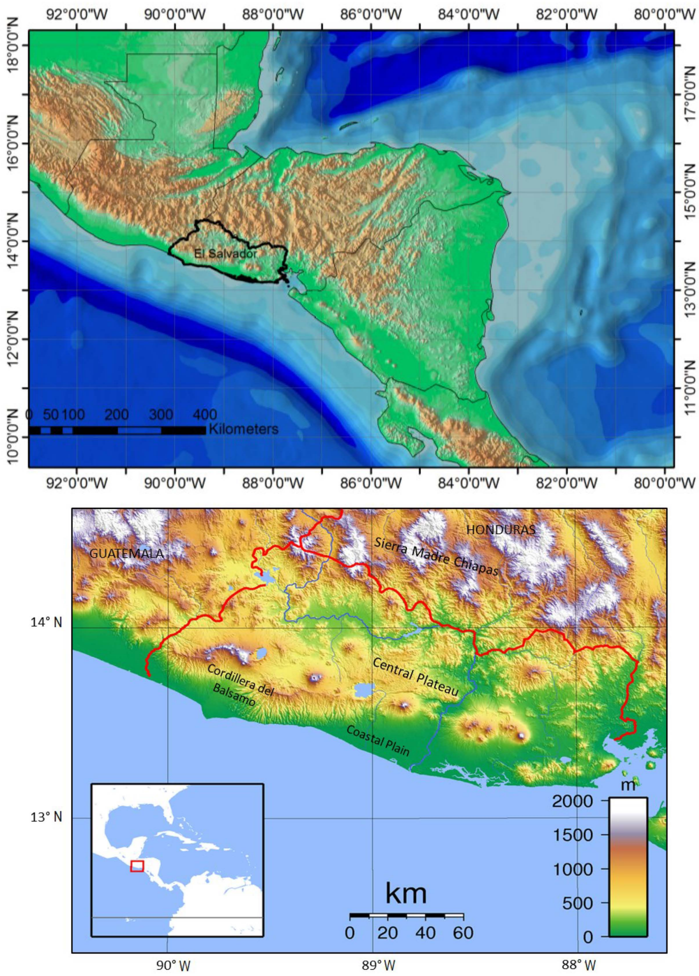

Figure 1. Location of the study area and topographic map.

The geography and geology of El Salvador provides fertile land for agriculture. El Salvador has become increasingly integrated into the global economy since the end of the civil war in 1992 [27], yet agriculture remains an important livelihood strategy and continues to have strong influences on the physical landscape. The total area of permanent crops in El Salvador has remained relatively constant since 1997 despite slight decreases in the agricultural labor force [28]. Cropland estimates indicate 54.7% of the land use land cover in El Salvador is under agricultural use (MODIS Land Cover Type product, LP DAAC [29]). Recent national concern regarding the frequency and extent of fires in El Salvador, their relation to agriculture, and their impact on forest cover has resulted in the development of a national commission on forest fires (Comision Nacional de Incendios Forestales, CNIF). The commission is composed of multiple government institutions with an objective of reducing fire occurrence.

3. Methods

3.1. Active Fire Data

We used one of the MODIS products, with 1-km spatial resolution; the fire hotspots series processed in the Collection 5 temporal thermal analysis active fire dataset with data from both the TERRA and AQUA satellites [30]. The daily set ranging from January 2001 to December 2014 was downloaded; this is available at FIRMS (Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data, Collection 5; [31]). Active fire detection is based on detecting the thermal signature of fires and provides the center of a pixel of a 500-m pixel where fires can be detected through their intense thermal emission (in the Mid InfraRed—MIR) [32,33]. This MODIS product provides a range of possible confidence levels. In order to decrease the chances of including observations that do not relate to fire incidences (e.g., associated with industry), we only used fires with confidence over 30 (medium and high confidence fires). Our final data product consists of a point file indicating the presence of active fires for each month of each year in the time series and also a fire spatial density map that indicates the number of fires detected per unit of area for the whole period analyzed and classified into 9 classes (Mean $\pm$0.5, 1, 1.5, 2 SD).

3.2. Rainfall Data and Standardized Rainfall Anomalies

A monthly cumulative rainfall dataset was derived from Tropical Rainfall Measuring Mission data (TRMM V V6 3B43 monthly precipitation product) from January 2001 to December 2014 at 0.25° (=25 km) spatial resolution. We calculated monthly standardized rainfall anomalies as the departure from the 2001 to 2014 mean for a month X in a year *i:* rainfall anomaly in month X*i* = ((rainfall in month X*i*) − (mean rainfall for all months X since 2001 to 2014))/(standard deviation of all months X from 2001 to 2014) where positive values indicate months wetter than the average rainfall for the 2001–2014 period and negative values indicate drier months than average [34].

3.3. Vegetation and Land Use Data

The vegetation data are monthly measurements of the Normalized Difference Vegetation Index (NDVI) from 2001 to 2014, with 1-km spatial resolution. These data are derived from observations recorded by the MODIS TERRA sensor (MOD 13). MODIS monthly NDVI data are generated using the 16-day vegetation index aggregated using a weighted average to produce a monthly composite. NDVI is based on the principal that vegetation is highly reflective in the near infrared and absorptive in the visible red [35]. This index is widely accepted over a range of geographic regions as an indicator of vegetation presence and properties [36–38]. Land use data are also derived from the MODIS land cover product MCD12Q1 (MODIS Land Cover Type product, LP DAAC 2013). This product has a 500-meter spatial resolution. We use the Land Type 1, based on the IGBP global vegetation classification scheme. For the years 2013 and 2014, we used the 2012 land use classification to explore the historical patterns of fires as associated with current land uses.

3.4. Analysis

Initial investigation of hotspots, rainfall and vegetation patterns was conducted by considering each pattern independently. Further analysis compares patterns across the three variables. The objective of this work is to explore general patterns of fire, rainfall, and vegetation at the national scale. We compare the mean annual and monthly values for fire, rainfall, and vegetation. This approach removes addressed variations in the spatial resolution of the datasets used for this analysis.

The monthly hotspots, rainfall (either total mm per month or anomalies) and vegetation patterns were analyzed to identify possible seasonality in the datasets. These time series were compared using cross correlation functions (CCFs) and lagged regressions [39,40]. The methodological approach used here is similar to that used by Koutsias *et al.* [41], who identified long-term wildfire and climate trends. Sample CCFs are helpful for exploring the relations between a number of time series and identifying lags of one time series, xt, that might be useful predictors of another time series, yt. The sample CCF between the two time series (xt and yt) is defined as the set of sample correlations between xt+h and yt for h = 0, ±1, ±2, ±3, and so on. Negative values for h indicate correlations between variable y and past values of variable x, while positive values for h indicate correlation between y and future values of x. Usually, the main interest is the behaviour at negative values of h, as is the case for this application. To determine whether the relationship between climate (rainfall or rainfall standardized anomaly) and vegetation was related to observed monthly and inter-annual variability in fire activity throughout the country, these variables were analyzed by means of lagged regressions using the lags suggested by CCF plots. A significance level of 0.05 was used.

4. Results

4.1. Temporal Variability of Rainfall, Hotspots and Vegetation

El Salvador has an annual cycle with peak rainfall occurring during May–October and the dry season extends from November–April (Figure 2). In the period analyzed, 2001 and 2006 were the driest years and 2010 and 2011 were the wettest (Figure 3).

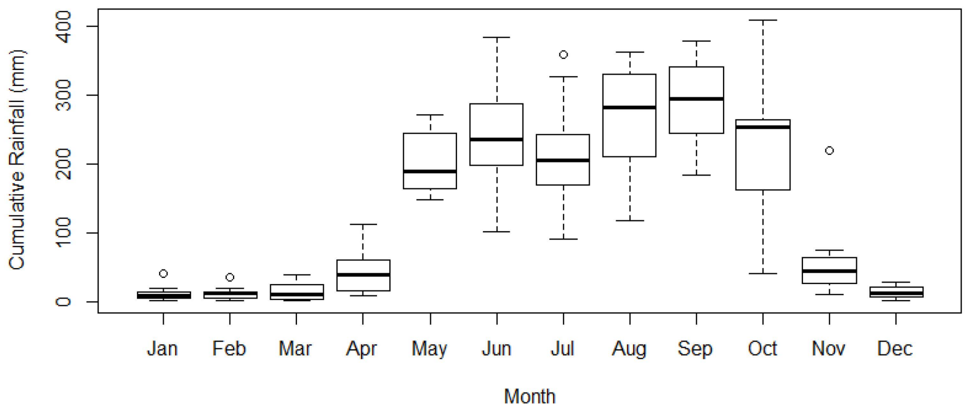

Figure 2. Monthly boxplots of cumulative rainfall (mm) in El Salvador between 2001 and 2014.

High annual variability exists for national fire observances in El Salvador between 2001 and 2014. The number of active fires detected ranges from 555 to 1500 (Figure 4), with an average number of satellite detected active fires per year over the 14-year period being 909.3 ± 304.4. The year having the highest number of satellite detected active fires was 2004 with 1500 fires; followed by 2013 with 1319 fires. The year with the lowest number of active fires detected (555) was 2008. The seasonality of active fire detection in El Salvador showed marked annual periodicity. The major peaks of fire hotspots on average occurred in two of the months of the dry season, March and April (Figure 5).

Particularly, in 2004 and 2013, high numbers of fire hotspots were detected for the months of March and April.

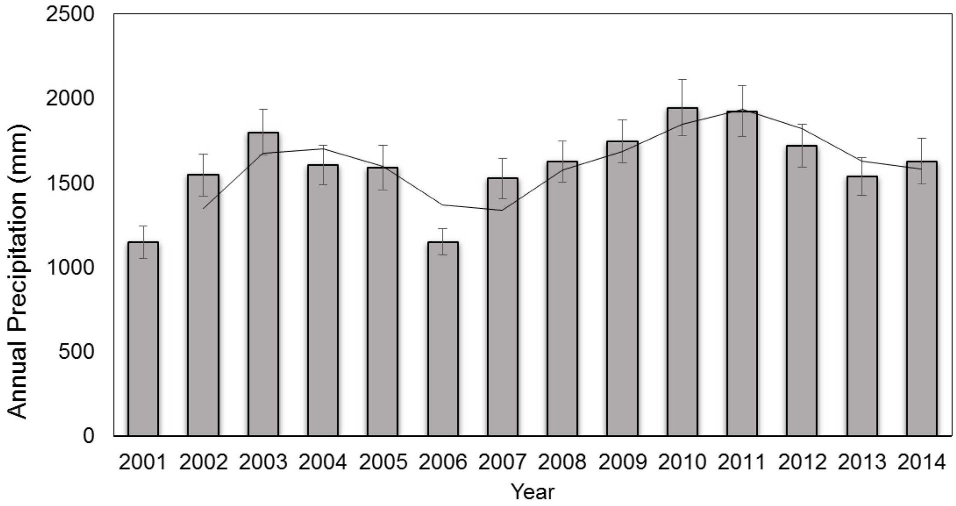

Figure 3. Annual precipitation in El Salvador between 2001 and 2014.

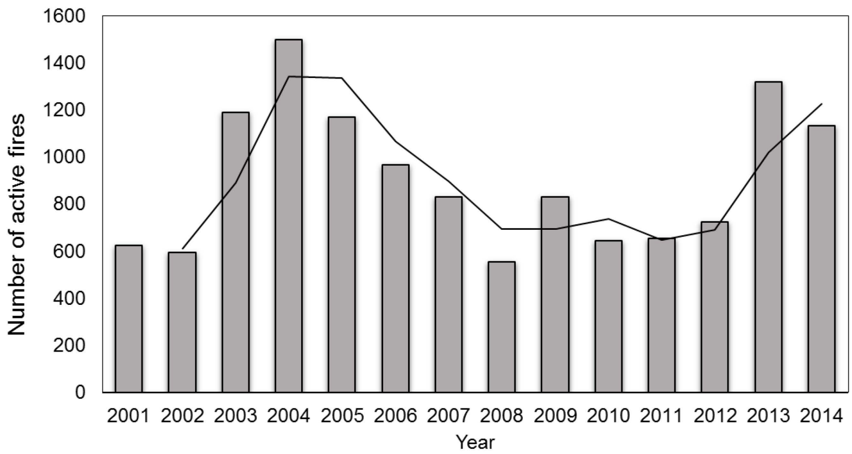

Figure 4. Number of satellite detected active fires per year in El Salvador between 2001 and 2014. The line shows a running average for the average annual values across the study time period.

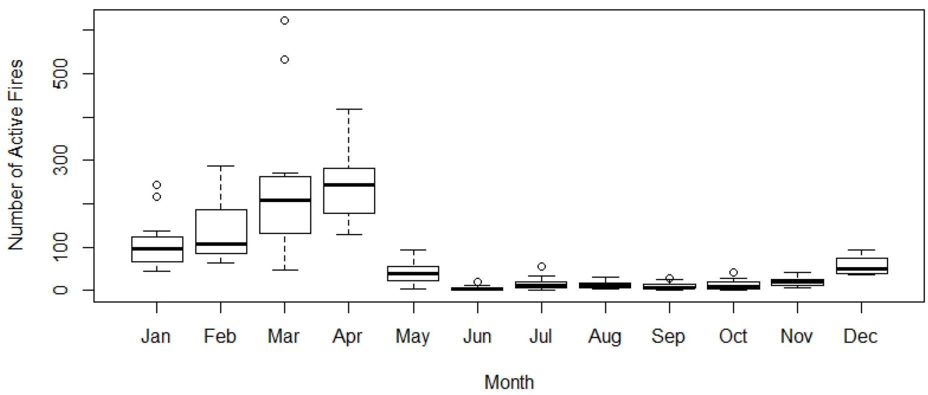

Figure 5. Monthly boxplots of satellite detected active fires in El Salvador between 2001 and 2014.

Variability also exists in vegetation observations (Figure 6). The average NDVI at the national scale across the 2001 to 2014 time period is 0.68 ± 0.01. The highest average NDVI observation was in 2007 (0.693), and the lowest occurred in 2010 (0.665) and in 2013 (0.663). The vegetation index (average national value) for El Salvador also showed a seasonal pattern (Figure 7). Except for November and December, the higher values of the vegetation index tend to occur during the months with a rainfall peak. A high value for the vegetation index was detected in March 2012 (0.59), while low values were detected in October and November 2010 (0.72 and 0.65, respectively).

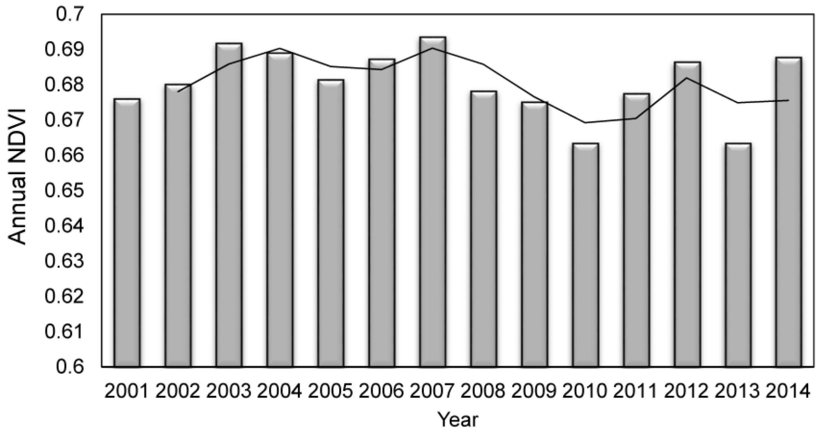

Figure 6. Average vegetation values per year and monthly boxplots of vegetation index (average national value) in El Salvador between 2001 and 2014. The line shows a running average for the average annual values across the study time period.

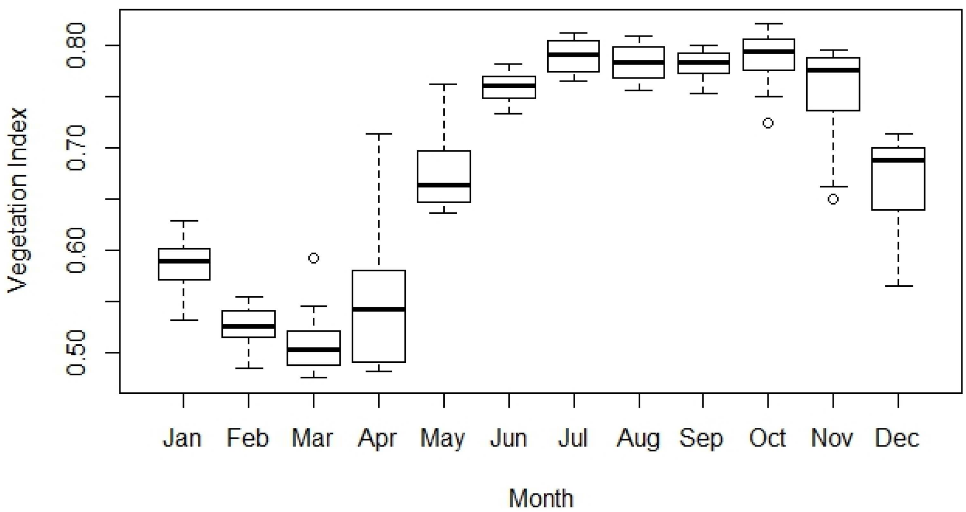

Figure 7. Monthly boxplot of vegetation index in El Salvador between 2001 and 2014.

The relationship between monthly number of fires, rainfall, rainfall standardized anomalies and vegetation was explored by analyzing cross correlation functions (Figure 8). The CCF plot between rainfall and fires showed negative correlations for lags 0, −1 and −2, and positive correlations for lags −6, −7 and −8, with slightly stronger correlation for lag −1. This reflects the seasonal pattern of the series and indicates that the peak period for the occurrence of fires is expected around two months after the start of the dry season, while a low occurrence of fires is expected around two months after the rainy season.

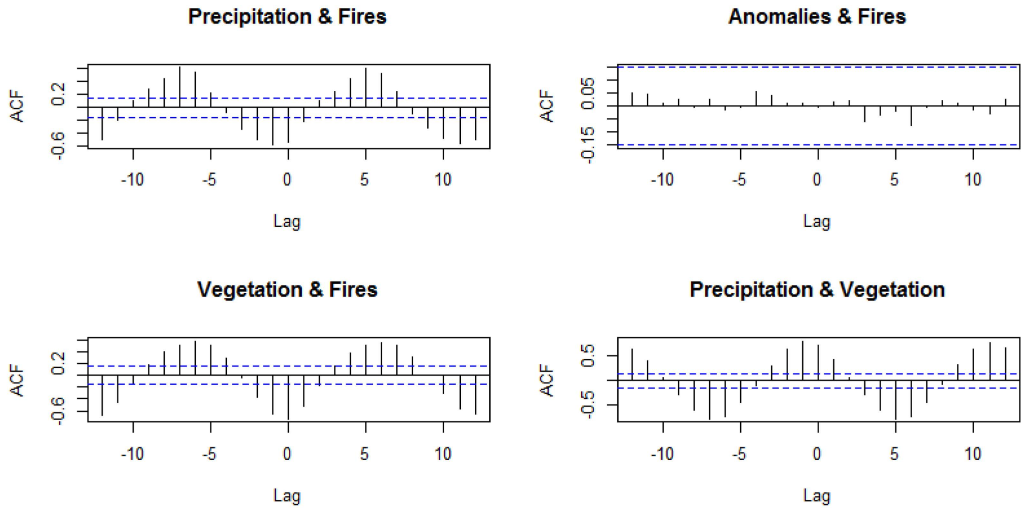

Figure 8. Cross correlation function (CCF) plots for El Salvador. *Y*-axis is the autocorrelation function (ACF), and the lag is shown on the *X*-axis.

The correlations between rainfall standardized anomalies and fires were very close to zero for all lags, suggesting that the association between rainfall and fires is due to the seasonal feature of both series. The CCF plot between vegetation index and fire showed a pattern similar to rainfall, indicating negative correlations for lags 0, −1, and −2, and positive correlations for lags −5, −6, −7 and −8, with slightly stronger correlation for lag 0. This feature suggests that a higher number of fires is detected around the months with low vegetation index and a low number of fires around the months with higher vegetation index.

The CCF plot between precipitation and vegetation showed positive correlations for lags 0, −1 and −2 and negative correlations for lags, −5, −6, −7 and −8, with slightly stronger correlation for lag −1. This indicates that peak values of vegetation index tend to occur around two months after the rainy season, which would be a period with a low detection of fires, while low values of vegetation index tend to occur two months after the dry season, which would correspond to periods with high detection of fires.

Lagged regression models were fitted based on the CCF plots. Models relating fire with only lagged rainfall variables, only lagged vegetation variables, and both lagged rainfall and vegetation variables were considered. A couple of similarly significant models were identified. All models showed significant coefficients for some lag of either rainfall or vegetation variables. The maximum r^2 found was 0.6289. The simplest significant model indicated that the number of fires for a particular month is associated with the number of fires from the previous month and vegetation index of the current month (r^2 = 0.5762). Significant regression coefficients for rainfall or vegetation variables with relative low r^2 indicate that fire variability could be only partially explained by climate variation. This means that other factors, such as anthropogenic drivers, may also influence the occurrence of fires in El Salvador.

4.2. Spatial Variability of Fires Across the Country and Land Use and Land Cover Types

Figure 9 illustrates the distribution of the occurrence of fire hotspots throughout the whole of El Salvador during the fourteen years (2001–2014). These results demonstrate high recurrence of fires repeating over the years, as well as areas where no fires tend to occur. The patterns indicate spatial clustering across the country in areas where the land use is categorized as cropland/agriculture (Table 1). Most fires tend to occur below 400 meters above sea level (m a.s.l.) and on average over the years, 64.8% of the fires are related to croplands with natural vegetation mosaic (51.3%) or crops (13.5%), followed by fires occurring in woody savannas (20.8%) and savannas (7.1%). A relatively low percentage of the fires were related to forested land (4.6%). Fire occurrences are related to roads; in fact, 70% of all fires occurred within 1 km of roads and the 95th percentile was within 2 km. The cross correlation functions were also used to examine the time series analysis per land use. The results from this analysis found that the correlations amongst vegetation, precipitation, and fires per land use reflected the same pattern as those seen when the data were considered at the national scale and discussed above.

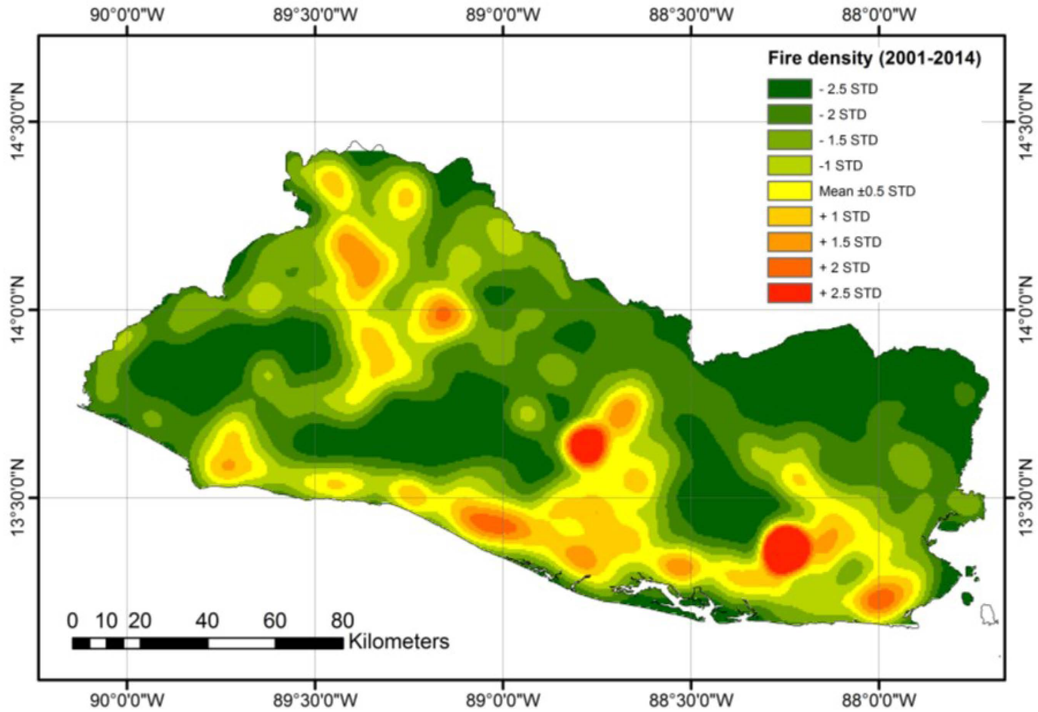

Figure 9. Spatial density of fire occurrence since 2001 in El Salvador.

Table 1. Area of land use/land cover types (average between 2001 and 2012 and standard deviation), number of fires detected per year and percentage of total number of fire occurrences (average between 2001 and 2014 and SD).

Land Use Land Cover Type	Mean Area (ha)	SD	Number of Fires (Mean 2001–2014)	SD	Mean % of Fire Occurrence	SD
Cropland/Natural vegetation mosaic	1,164,200	175,681.5	464.6	152.69	51.3%	0.023
Woody savannas	768,594	100,406.3	189.9	67.31	20.8%	0.016
Croplands	199,715	97,656.4	122.1	40.36	13.5%	0.015
Savannas	67,817	46,468.0	64.2	22.69	7.1%	0.008
Deciduous Broadleaf forest	34,071	13,572.8	24.9	15.85	2.6%	0.008
Evergreen Broadleaf forest	139,573	7110.2	12.1	5.19	1.3%	0.004
Grasslands	4183	3008.4	11.5	7.59	1.2%	0.005
Mixed forest	12,821	3915.4	5.8	2.26	0.7%	0.003
Other	63,625	6966.4	14.1	9.55	1.6%	0.011

5. Discussion

Climate has been identified, regionally and globally, as the primary driver of large fires [7]. El Salvador is a small country with a reported 51 km^2 of land burned as detected by remote sensing [18]. We used satellite data of active fires in El Salvador to explore fire patterns, including smaller fires, likely related to local agricultural practices to be integrated in the analysis. We also used monthly precipitation data to study the climatic effects on burning activity in El Salvador. This temporal resolution of climate data is appropriate for examining the relationship between fires and climate (see for example [14]). Our results indicate that in El Salvador, the spatial pattern and interannual variability of fires are linked to climate, specifically to monthly precipitation patterns. The results show that burning activity increases during the driest months (November to April) and before the wettest months (May–October) and that these peak burning periods generally have a two month lag with precipitation. Seasonal maximum in fires corresponds to the period where vegetation is most moisture stressed within the annual cycle. Furthermore, our results confirm the fact that interannual variability in climate has some impact on fire activity from year to year, in agreement with other reported couplings in climate oscillations [7,34,42]. Two years, 2004 and 2013, were particularly high in fire occurrence and these years follow years of high vegetation presence and high mean annual rainfall (around 1700 mm for 2002/2003 and over 1700 mm from 2010 to 2012, respectively). This possibly indicates that high rainfall in the years prior (2002 and 2003 present a moderate El Niño) contributed to high fuel presence and peak fire occurrence in 2004. The El Niño phenomenon favors drought in El Salvador [44], which means that the weak El Niño in 2004 may have intensified fire ocurrence. On the other hand, the years of 2010 to 2012 had a weak to moderate La Niña, which could have had an opposite impact on fire occurrence in the year of 2013. After a wet period (over 1700 mm), fire increased possibly due to a rapid onset of drought and the impact of this rapid drought on vegetation. Similarly, the low fire occurrence in 2006 may be related to the relatively low NDVI values observed in 2005, which potentially contributed to low fuel availability in 2006. The years of 2005 and 2006 also presented a weak El Niño, with 1500 mm and 1150 mm of total precipitation, respectively.

Spatial variability at the national scale can be observed in terms of both fire activity and vegetation dynamics. The spatial patterns of fire occurrence indicate that fires tend to occur in lowland areas where the establishment of agriculture is evident in the land cover data. In these areas, agricultural plots are small in scale (typical plot size is between two and three hectares) and are interspersed with expansive cultivations of sugar cane. Fires also occurred within close proximity to roads, a physical feature the presence of which is often interrelated with agricultural land use practices and landscape modification [43,45–48]. These spatial patterns confirm that El Salvador follows the widespread use of fire as a tool for managing agricultural lands in other regions of Latin America and the developing world [10].

In addition to the spatial pattern of high fire occurrence in agricultural land use zones within El Salvador, fire occurrence does exist within some forested portions of the landscape. In a country with low forest cover and few remaining forest fragments, the presence of fires in forested areas of the landscape or near the edges of forested areas deserves further research. These fires may be indicative of localized deforestation occurring in a country that has previously been reported to be undergoing a reforestation process at the national scale [24]. Regardless of spatial association with land use, fires have significant implications for atmospheric emissions; however, fires occurring within forested areas or along forest edges have additional implications with regard to forest degradation, particularly if El Salvador is to eventually consider becoming a Reducing Emissions from Deforestation and forest Degradation (UN-REDD) partner country.

6. Conclusions

This work could be extended with future research by exploring the role of surface temperatures and wind patterns on fire occurrence and fire spread. A general warming and drying trend in Central America indicates that increases in fire occurrence are likely, and as such, anthropogenic fire could be intensified or have a broader spatial reach due to changes in the biophysical conditions within El Salvador. For example, fire that originates on a farm may be shaped by wind patterns, increasingly dry conditions, and corresponding modifications to fuel load, resulting in the fire moving beyond the perimeters of the farmland into nearby forests. Additional extensions of this work could also expand the examination of social and economic factors that determine fire occurrence and develop a fire risk model to be used by regional authorities. Xystrakis *et al.* [49] examines the intertwinement of socioeconomic factors and burn patterns. Their work highlights the relationship between fire processes and decision making related to land use and socioeconomics. Similarly, the results presented in this work highlight a clear spatial pattern of fires predominantly existing in agricultural lands. The objective of this work is to present an initial explanation of the general pattern of fire occurrences and to point to future directions for further investigation. The data analysis shows an association between fires and rainfall (dry months associated with high detection of fires). Additionally, we rely only on a broad classification of land use as an indicator of social factors affecting fire occurrence. One conclusion from this work is that other factors, in particular social and economic factors, are needed to explain the overall variability of fire occurrences. The scope of this work does not extend into considering the decision-making process that land managers use to determine if, when, and how fire is used as a tool for agriculture. For example, we do not differentiate between fires that are used for initiating agricultural cycles and those used for stimulating aboveground biomass growth for livestock foraging. These examples emphasize the importance of continued research, which disentangles the social and climatic factors driving fire occurrence, while also underscoring the need to create a baseline understanding of current fire occurrence patterns in order to better prepare for future conditions that will influence fire patterns.

This initial examination of fire, vegetation and precipitation patterns serves as a starting point for understanding the role of fire in El Salvador's landscape. The results indicate that anthropogenic fires interact with climate dynamics. This suggests that, from a planning and policy perspective, El Salvador will need to consider both the anticipated future climate conditions and the role that fire has as a local land management tool when determining policies aimed at shaping the quantity, location and timing of burning.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4433/7/2/26/s1.

Table S1. Area (in hectares) of each land use land cover category per year.
Table S2. Percentage of landscape in each land use land cover category per year.
Table S3. Number of satellite detected active fires per land use land cover category.
Table S4. Percentage of fire ocurrence per land use land cover category.

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Author Contributions: Dolors Armenteras and Cerian Gibbes conceived the idea, designed the analysis, performed data analysis for spatial and temporal patterns and wrote the manuscript; Juan Sebastian Espinosa prepared the information and performed some of the pattern analysis, Carla Vivacqua analyzed the time series data; Wania Duleba, Fabio Goncalves and Christopher Castro supported the climatic data analysis. All authors contributed to revising the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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