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# Modeling and Mapping Forest Fire Occurrence from Aboveground Carbon Density in Mexico

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## Introduction

The spatial fire occurrence maps estimates could be integrated into operational GIS tools for assistance in fire danger mapping and fire and fuel management decision making. Some studies have proposed that the occurrence of forest fires increases with increasing levels of forest productivity, biomass, basal area or other biometric characteristics (Botequim, *et al.* 2013). Other studies support the intermediate fire-productivity hypothesis, suggesting that the highest wildfire activity occurs in areas with intermediate net primary productivity (Pausas and Ribeiro, 2013). Additionally, the effects of biomass on fire occurrence can largely vary by climatic location or ecoregion (Littell, *et al.* 2009). Some studies have compared average fire frequencies for contrasting ecoregions from regional and national (Holz, *et al.* 2012) to global scales (Pausas and Ribeiro, 2013). Globally, the country of Mexico ranks highly among areas of largest fire activity (Chuvieco, *et al.* 2008). Mexico has experienced a marked increase in the fire weather season due to climatic change (Jolly, et al. 2015). Furthermore, fire activity in the North American region is projected to increase under climate warning (Flannigan, *et al.* 2013). Previous studies in Mexico have related fire occurrence with vegetation type, mainly at a local scale (Avila-Flores, *et al.* 2010). Some studies have documented differences in fire occurrence by ecoregion at a national level (Zuñiga-Vazquez, et al. 2018), but, in spite of medium resolution biomass maps from satellite images in Mexico being available at national (Cartus, *et al.* 2014) and at local scales (López-Serrano, *et al*. 2016), no study has attempted to relate the spatial patterns of fire occurrence with biomass in Mexico. The present study summarizes the results from Briones-Herrera *et al.* (under review) of model and map the forest fire occurrence, as observed from fire suppression records, from aboveground carbon density in Mexico, at 1 km resolution.

## Materials and methods

*Study area and forest regions, Aboveground Carbon Density data (AGCD) and forest Fire data*

The regionalization of the country was based on the regions proposed by Vega-Nieva, *et al.* (2018), which was based on the North American ecoregions map (North American Level 3 Ecoregions Map, EPA, https://www.epa.gov/ecoresearch/ecoregions-north-america), together with previous analysis of the spatial patterns of fire occurrence in the country (Pompa-Garcia, *et al.* 2018). In addition, in this study we included two additional regions, Northern scrubland and chaparral, based on the land use map of the National Institute of Geography and Statistics (INEGI in Spanish, Land Use Map Series V, 1:25000 http://www.inegi.org.mx/geo/contenidos/recnat/usosuelo/). This resulted in a total of seven regions for analysis: CHAP: chaparral forests; N: North shrub land forests; NW: Northwest forests; NE: Northeast forests; C: Center forests; SC: South-Center forests and SE: Southeast tropical forests (figure 1).

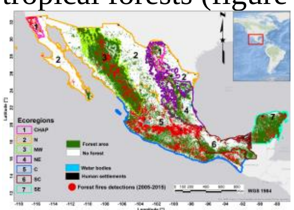

**Figure 1: Map of ecoregions. Source: modified of Vega-Nieva, *et al.* (2018) and considering INEGI Land Use Map Series V (2011), 1:25,000. Where: CHAP: chaparral forests; N: North forests; NW: Northwest forests; NE: Northeast forests; C: Center forests; SC: South-Center forests; SE: Southeast tropical forests, respectively. Forest and no forest areas are shown in green and white, respectively; human settlements in black and water bodies in blue, respectively, according to INEGI Land Use Map Series V (2011), (1:250,000). Forest fires detections (2005-2015) represent the fire suppression records by CONAFOR in the period of study.**

The aboveground carbon density map (AGCD) from the study of Cartus et al. (2014) was utilized, because of its public availability. This map was obtained from Landsat images, radar data from ALOS PALSAR, calibrated with ground data from the Mexican National Forest and Soil inventory (Cartus *et al.* 2014). The AGCD map was rescaled from 30 × 30 m to 1,000 x 1,000 m wall to wall for scale matching whit the layers used in the ongoing Mexican Fire Danger System (Vega-Nieva *et al.* 2018). A low pass filter with a moving window of 3 x 3 pixels, using the package included in Spatial module of ERDAS IMAGINE software, Version 2014, (ERDAS, 2014) was applied to the AGCD map. The fire suppression records database from the Mexican Government Forest Agency CONAFOR from the period 2005 to 2015 was utilized. The forest fires records in water bodies, cities and agriculture were excluded for the analysis based in the land use map from INEGI (2011). The database comprised a total of 53,000 fire suppression records in the period of study.

*Statistical analysis*

*Observed fire occurrence by AGCD, modeling and mapping fire occurrence from AGCD*

We firstly calculated the total number of forest fires, termed NFTi, for every region "i".
The aboveground carbon density (AGCD), in Mg C ha-1, was retrieved for every fire suppression record, using the extract multiple values to points tool in ArcGIS 10.0 (ESRI 2010) software. For every forest region (i), the fraction of fire occurrence recorded by AGCD value (j) was calculated following equation. 1:

$$FOB_{ij} = NF_{ij} / NF_{Ti} \quad (1)$$

**Where: FOB: Fire Occurrence index by Biomass level (fraction of the number of fires recorded at a forest region i for every AGCD value j); NFij= number of forest fires recorded a forest region i for every AGCD value j; NFTi= total number of forest fires recorded for the i region.**

The two-parameters Weibull probability density function –PDF-model (Weibull, 1951) was tested to predict FOB from AGCD for every region following equation 2:

$$FOB_{ij} = [(c/b)\ (AGCD_{ij} / b)]\ \hat{}(c-1) \cdot \exp\ [(-AGCD_{ij} / b)\ \hat{}c] \qquad (2)$$

**Where FOB: Fire Occurrence index by Biomass level for every AGCD value j at every forest region i (equation 1); AGCD is the observed aboveground carbon density value j for every i region; and b and c are the scale and the shape parameters of the model coefficients to be estimated, respectively. The models to predict observed FOB from AGCD (eq. 2) were fitted with non-linear regression (NLS) using the package nls of the software R (R Core Team, 2017). In addition, the nonlinear extra sum of squares method (Bates and Watts, 1988, pp. 103-104) was used to assess whether the models were significantly different among different regions.**

## Results

*Total number of forest fires by region and modeling and mapping fire occurrence from AGCD*

For the period of study, the total number of forest fires (NFTi) in the regions of Northwest and Northeast NFTi were 6,677 and 670, respectively. This is equivalent to a fire density of 244 and 41 fires per 10,000 km2 of forest land in every region, respectively. The Center region had the largest number of fires, with an NFTi of 13,220 records, equivalent to a fire density of 395 fires per 10,000 km2 of forest land. In the temperate and tropical forest of the South, the NFTi were 606 and 1,062, equivalent to fire densities of 133 and 83 fires per 10,000 km2, respectively. The chaparral and North regions had a lower number of fires compared with other regions, with 486 and 91 fires in the period of study, equivalent to fire densities of 19 and 8 fires per 10,000 km2, respectively. The estimates and the confidence interval of the Weibull PDF parameters and the values of the goodness-of-fit statistics for each region are shown in table 1. The best goodness-of-fit statistics were obtained for C and NW-NE regions with R2 values of 0.95 and 0.98, respectively and RMSE values of 0.002 and 0.003, respectively. On the other hand, the lowest values of the goodness-of-fit statistics were obtained for N region with a R2 value of 0.48 and a RMSE value of 0.029 (table 1).

| Ecoregions | Coefficients | | Goodness of Fit | | |
|---|---|---|---|---|---|
| | b | C | R2 | RMSE | Bias |
| CHAP | 21.45 (± 0.83) | 1.97 (± 0.12) | 0.715 | 0.008 | 0.0011 |
| N | 17.85 (± 0.88) | 3.81 (± 0.55) | 0.487 | 0.029 | 0.0045 |
| NW_NE | 27.22 (± 0.16) | 3.63 (± 0.06) | 0.980 | 0.002 | 0.1 x 10-5 |
| C | 33.12 (± 0.30) | 3.02 (± 0.07) | 0.953 | 0.003 | 0.1 x 10-4 |
| SC | 25.85 (± 0.80) | 2.53 (± 0.16) | 0.720 | 0.008 | 0.0002 |
| SE | 31.34 (± 0.57) | 2.69 (± 0.11) | 0.839 | 0.005 | 0.0011 |

**Where: CHAP: chaparral forests; N: North scrubland forests; NW_NE: Northwest and Northeast forests; C: Center forests; SC: South-Center forests; SE: Southeast tropical forests; b and c are the estimates of the two parameters Weibull PDF fitted for prediction of FOB from AGCD (confidence interval in brackets); R2: coefficient of determination; RMSE: mean square error (in FOB units); Bias: model bias (in FOB units).**

The curve of observed fire occurrence by biomass level FOB for each forest region is shown in figure 2, together with the predicted values, against AGCD. Predicted against observed FOB values and the related goodness-of-fits statistics are shown in figure 3. In the chaparral and North scrubland forests (figure 2a and 2b) the highest values of FOB occurred at low values of AGCD (from 7 to 25, 10 to 22 Mg C ha-1, respectively). For the regions of the combined Northwest and Northeast and South Centre (figures 2c and 2e), highest values of FOB were related with medium values of AGCD (from 15 to 35 Mg C ha-1), with a steeper distribution for the NW and NE compared to SC. In the Center and Southeast regions, (figure 2d and 2f), the highest FOB values were observed in slightly higher AGCD values, ranging from 20-22 to 35 Mg C ha-1, with a flatter distribution for SE. Lower fire occurrence was observed at the highest biomass levels for all regions. The map of predicted FOB for Mexico based on the fitted models is shown in figure 4. A good agreement can be seen between predicted FOB values mapped and the historical fire suppression records spatial distribution in the country.

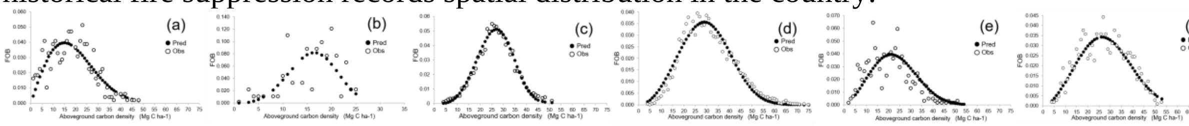

**Figure 2. Predicted and observed Fire Occurrence by Biomass level (FOB) against Aboveground carbon density (AGCD) (Mg C ha-1) for each region CHAP (a); N (b); NW and NE (c); C (d); SC (e) and SE (f); Pred: predicted values; Obs: observed values.**

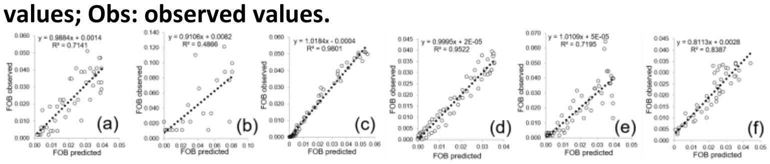

**Figure 3. Predicted versus observed Fire Occurrence by Biomass level (FOB) for the regions CHAP (a); N (b); NW and NE(c); C (d); SC (e) and SE (f).**

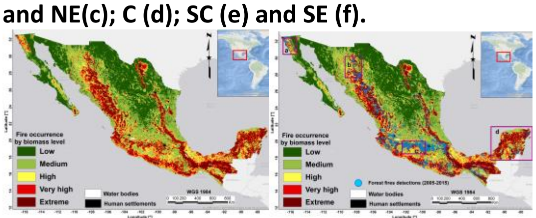

**Figure 4. (left) Map of normalized Fire Occurrence by Biomass level (FOB); where low, medium, high, very high and extreme represent FOB values of <1, 1-25, 25-50, 50-75 and >75 % respectively. (b) Location of suppressed fires in the study period. The regional detailed windows included in the right figure are analyzed in detail in Briones-Herrera, *et al*. (under review).**

## Discussion

*Total number of forest fires by region and modeling and mapping fire occurrence from AGCD*

The differences in the total number of fires ($NF_{Ti}$) between forest regions confirms previous observations of fire activity in Mexico (Zúñiga-Vazquez, *et al*. 2018) and agrees with observations from other countries where fire activity varied by ecoregion (Huesca, *et al.* 2014). The higher observed wildfire density in the Northwest (NW), compared to the Northeast (NE) agrees with Pompa-Garcia, *et al*. (2018). This tendency is also consistent with higher occurrence in the Western compared to the Eastern US (Nagy, *et al.* 2018), coinciding with higher fuel moisture in the East coast (Burgan, 1998), similarly to that observed from MODIS active fires in Mexico (Vega-Nieva, *et al.* 2018). The highest fire suppression records in the C region, with a fire density three times higher than the SC region, coincides with observations from Pompa-Garcia, *et al*. (2018) and Zúñiga-Vazquez, *et al*. (2018) who also reported the biggest cluster of fire suppression records in the forests of the C region. A large anthropogenic influence is likely explaining that high fire occurrence (Vega-Nieva, *et al.* 2018). Different relationships between productivity and fire occurrence agrees with works that have developed separated models for prediction of fire occurrence by ecoregion (Huesca, *et al.* 2014). For the chaparral region, (figures 2a), a large percentage of fire suppression records occurred at AGCD values in the range 5-25 Mg C ha-1, with the highest values of fire occurrence found in the range 15-25 Mg C ha-1, approximately corresponding to fuel loads from 30 to 50 t/ha. Unlike the chaparral region, temperate pine and oak forests in the NW, NE (figure 2c) and C regions (figure 2e) did not experience a large fire occurrence for AGCD <15 Mg C ha-1. In these regions, low biomass areas are mainly covered by xerophitic shrublands (INEGI, 2011) which, unlike chaparral, are characterized by lower fuel continuity and generally lower fire propagation hazard (Rodríguez-Trejo, 2014). The temperate forests, the highest biomass areas, with lower fire occurrence, correspond to dense old-growth forests, mainly located from middle to high elevations. This fuel structure limits wind penetration and sunlight incidence, maintaining low surface fuel loads and microclimatic and fuel structural conditions that hamper the occurrence of high severity fires (Cortés Montaño, *et al*. 2012). The response of fire occurrence in tropical SE forests to forest biomass might be partially explained by taking into account differences in forest structure, microclimatic conditions and human influences on ignition. Highly productive areas of highest cover tend to be fire-limited by fuel moisture with wet fuels preventing ignition, together with a lower fire spread potential (Kahiu and Hanan, 2018). In tropical forests, lower biomass areas are more connected to active forest degradation at landscape level, including slash and burn activities, which are important causes of fire occurrence in the SE region (Rodríguez-Trejo, 2014).

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