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Artículo

Relación espaciotemporal de puntos de calor con superficies agropecuarias y forestales en San Luis Potosí, México

Time-space relationship between hotspots and agricultural and forest surface areas in *San Luis Potosí* State, México

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Resumen

Es importante analizar la dinámica entre coberturas de uso de suelo para comprender las relaciones existentes en las superficies donde se presentan los cambios. También, en ocasiones, las modificaciones de cobertura son ocasionados por actividades humanas, como los incendios utilizados en actividades agrícolas. El objetivo de este trabajo fue analizar espaciotemporalmente si existe una relación significativa entre las superficies agrícolas, pecuarias (pastizales) y forestales con la incidencia de puntos de calor, en San Luis Potosí, México. Varios autores han utilizado la percepción remota y los SIG para modelar coberturas de uso de suelo, y han aplicado diversos algoritmos con este propósito. Para estimar las superficies (forestal, agrícola y pecuaria) se aplicó una clasificación supervisada a escenas *Landsat* 5 TM y *Landsat* 8 OLI. Además, se integraron dichas superficies en modelos no lineales: polinomio (2° orden), exponenciales y potenciales, así como multivariados para estimar puntos de calor; lo que resultó en un aumento sustancial en los coeficientes de determinación en los segundos modelos. En cuanto a los resultados, es posible predecir la ocurrencia de puntos de calor de una variedad de áreas bajo la agricultura, la ganadería y la silvicultura. En este caso, la superficie forestal fue la variable más significativa, seguida de la superficie ganadera. Se concluye que existe una relación entre la presencia de puntos de calor con tierras agrícolas en el área de estudio y se puede predecir la ocurrencia de puntos de calor basados en variaciones de las tierras agrícolas, pecuarias y forestales.

Palabras clave: Clasificación supervisada, correlación, *Landsat*, modelos no lineales, tendencia, uso de suelo.

Abstract

It is important to examine the dynamics between land use coverages in order to understand the existing relationships in the areas where changes occur. Also, sometimes the cover changes are caused by certain human activities, such as the fires used in agriculture. The objective of this study was to spatiotemporally analyze whether a significant relationship exists between the agricultural, livestock (grasslands) and forest surface areas and the incidence of hotspots, in the state of *San Luis Potosí*, Mexico. A great number of authors have used remote sensing and GIS for modelling land use cover, and they have applied several algorithms for that purpose. For estimating the coverages (forest, agriculture and livestock), a supervised classification to Landsat 5 TM and Landsat 8 OLI scenes was applied. In addition, agricultural, livestock and forest surface areas were incorporated into non-linear models (Polynomial (2^{nd} order), exponential and potential) and multivariate models for estimating hotspots, which resulted in a substantial increase in the coefficients of determination in the latter. As for the results, it is possible to predict the occurrence of hotspots in a variety of agricultural, livestock and forest areas. In this case, the forest areas were the most significant variable, followed by the livestock areas. The results obtained suggest that there is a relationship between the presence of hotspots and the agricultural land in the study area, and it is possible to predict the occurrence of hotspots based on the variations of agricultural, livestock, and forest lands.

Key words: Supervised classification, correlation, Landsat, nonlinear models, trend, land use.

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Introduction

Fires are one of the most important factors impacting forest resources, since, for example, they affect vegetation cover (Gallegos *et al.*, 2014; Bautista and Rodríguez, 2017), the structure of forest ecosystems (Alanís *et al.*, 2018), and the natural regeneration of the tree stand (Juárez-Martínez and Rodríguez-Trejo, 2003).

Although their causes are diverse, in Mexico they are the result of the interaction of anthropogenic activities with environmental factors that define their behavior (Ibarra-Montoya and Huerta-Martínez, 2016). Moreover, it is estimated that 97 % of the fires in Mexico are caused by human activities (Cruz *et al.*, 2017). These fires result predominantly from burns related to agricultural and livestock activities, in which fire is used to prepare land for sowing and grazing (Flores *et al.*, 2016). This implies that the larger the areas dedicated to these activities, the more likely they are to cause fires.

However, the models to assess fire incidence in Mexico do not include anthropogenic activities, since they are mainly focused on forest fuel load, and some consider environmental variables (Chávez *et al.,* 2016).

However, some models involve agricultural variables such as the number of livestock heads (density), for determining areas with potential for fire development (Ibarra-Montoya and Huerta-Martínez, 2016). In spite of it, there are currently no studies that relate the dynamics of agricultural and forestry areas to the incidence of fires. The integration of field data with technologies such as Geographic Information Systems and Remote Sensing would allow modeling this trend (Gollberg *et al.*, 2001).

Accordingly, the objective of this study was to analyze whether there is a time-space relationship between agricultural, livestock (pasture) and forest areas and the occurrence of hotspots. Based on this, it was hypothesized that the increase in the area dedicated to agricultural activities is related to the increase in the number of hotspots and the variation of forest areas in the state of *San Luis Potosí*.

Materials and Methods

The study was carried out in the state of *San Luis Potosi*, north-central Mexico, between 21°10' and 24°32' N and 98°20' and 102°18' W (Figure 1), where, according to figures from the National Forest and Soil Inventory (Conafor, 2014), the forest area is 4 314 6321 ha (71 % of the state's surface). The vegetation there corresponds to three major ecosystems: temperate forests, tropical forests and vegetation of arid and semi-arid zones. On the other hand, 851 004 ha, which amount to 14 % of the total area of the state, are dedicated to agricultural activities (INEGI, 2015), whereas 725.9993 ha (12 %) are grasslands.

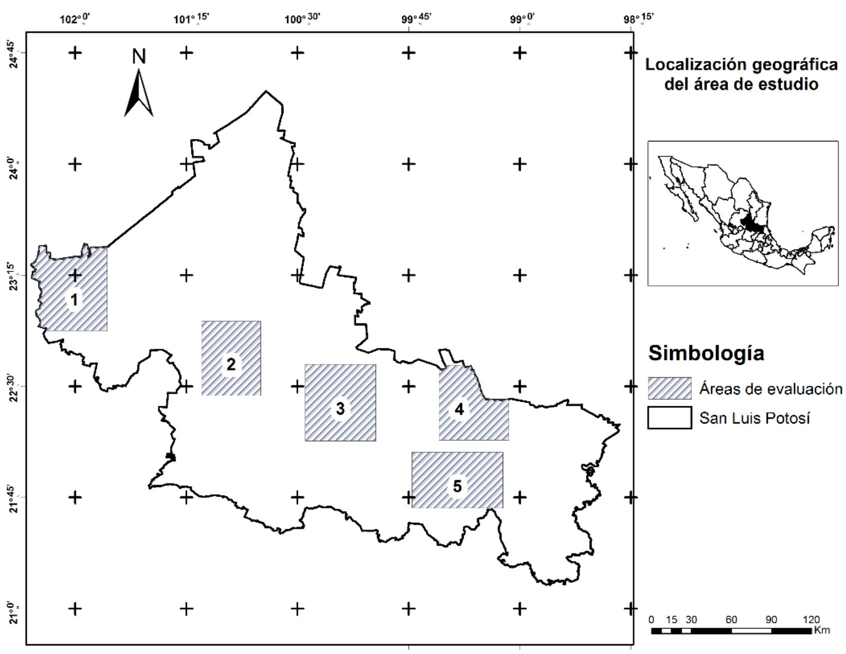
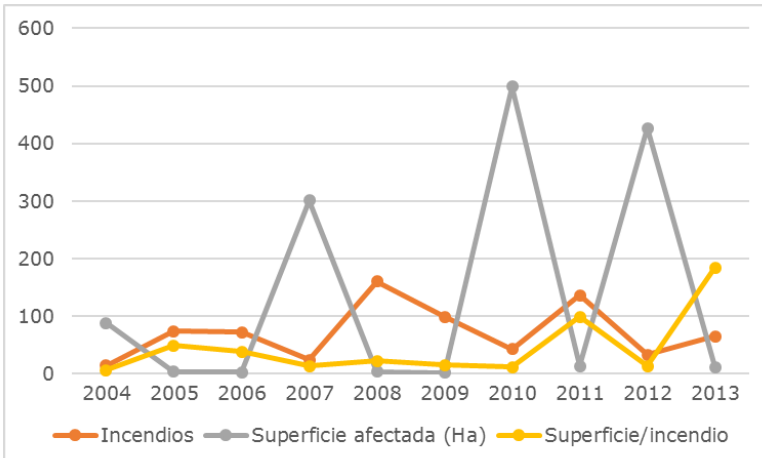


Figure 1. Geographical location of the state of *San Luis Potosí* and location of the evaluation areas.

The relationship between changes in land cover and the incidence of hotspots was analyzed defining five evaluation areas that met two main criteria: 1) that hotspots (HS) were detected, and 2) that forest vegetation, as well as agricultural or livestock areas (pastures) were located.

Regarding fires (Figure 2), *San Luis Potosí* annually records an average of 72 events, affecting an area of 3 821 ha, with an average size of 53 ha per conflagration (Conafor, 2014). The fire season coincides with the dry season, with prolonged periods of drought, mainly from January to June.



Source: Conafor (2014).

Figure 2. Fire dynamics in the state of *San Luis Potosí*

For the 2010-2017 period, geographic information by evaluation area was obtained for each one of the HSs from the report generated by the National Commission for the Knowledge and Use of Biodiversity (Conabio), for which image processing with AVHRR and MODIS was utilized (Muñoz-Robles and Santana-Arias, 2018). In this way, the spatiotemporal occurrence of HSs was determined and related to the dynamics of variations in forest, agricultural and livestock areas.

Land use changes in the evaluation areas were analyzed by determining changes in forest, agricultural and livestock areas, using satellite images corresponding to row/path: 27/44, 27/45, 28/44 and 29/44, which were downloaded from the U.S. Geological Survey server: a) Landsat 5TM, for the years 2010 and 2011; and b) Landsat 8 OLI, for 2013 to 2018. We did not work with the 2012 image because it failed to provide information for many areas. Since the difference between forest, agricultural and livestock areas can be best appreciated in the dry season, the Landsat images included were from the months of January to March.

Likewise, the combination of 5-4-3 bands was the one that allowed discriminating in more detail the agricultural, forest and livestock areas, which facilitated establishing the training areas (Cartaya *et al.*, 2015) to apply the supervised classification.

The training areas were defined based on information on land cover and land use recorded in *Inegi* Series VI (2016). These data also served as a basis for differentiating the following land covers: 1) bodies of water; 2) agricultural areas; 3) pasture lands; 4) urban areas; 5) vegetation or forest areas, and 6) areas without vegetation. Having carried out this classification under supervision, the surface area of each category in the evaluation areas was determined, and subsequently the annual dynamics of the examined canopies were established. The classes "urban areas" and "bodies of water" were eliminated in order to restrict the analysis to the coverages of interest.

The dynamics of the trends in the annual variations of the agricultural, forest and livestock areas were defined by establishing the best-fitting simple regression models, as well as their corresponding equations. For example, an analysis was carried out of whether the increase in agricultural areas led to a decrease in forest areas. Subsequently, a multivariate analysis was used to define the trends of the hotspots with respect to variations in the surface areas of forest, agricultural and livestock areas, by means of linear and nonlinear multiple regression models.

Results and Discussion

First, the spatial distribution of hot spot incidence was analyzed (Figure 3).

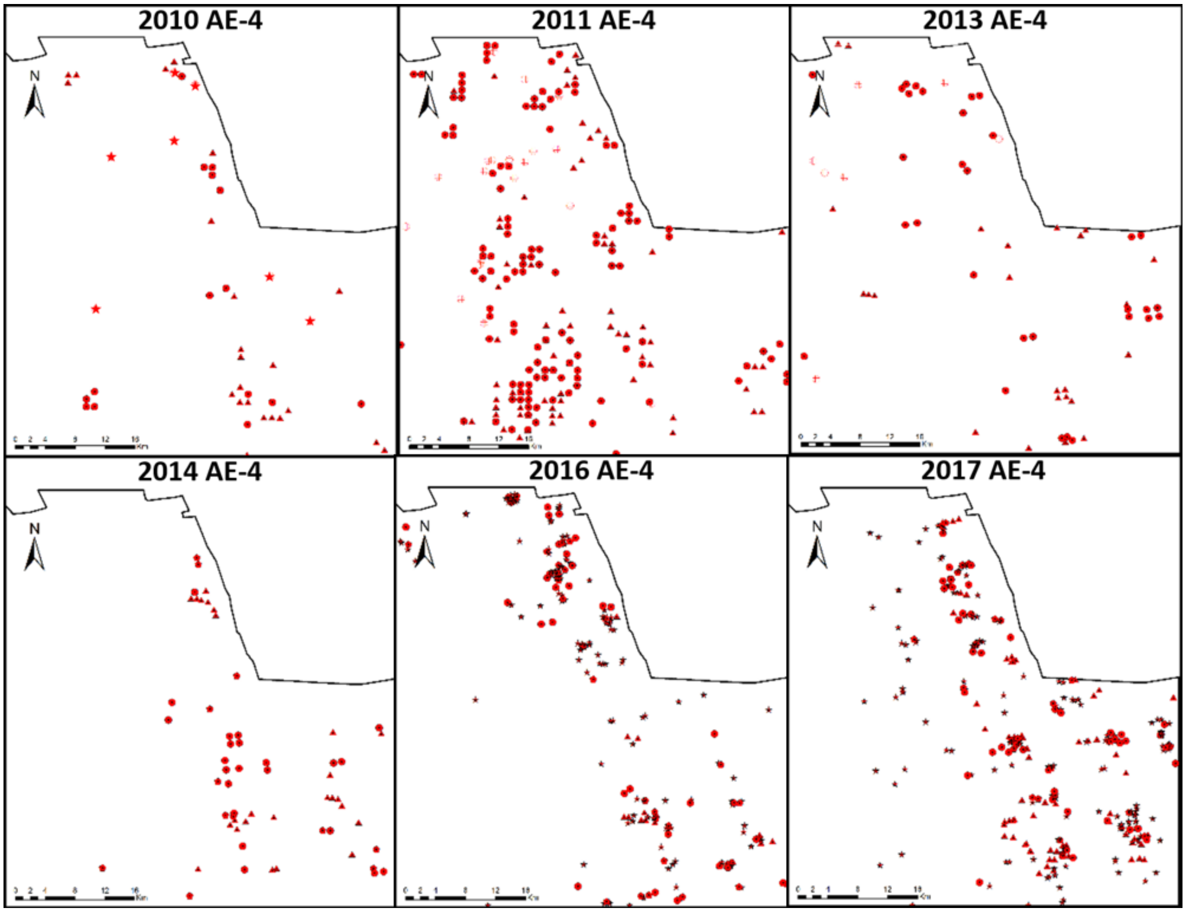


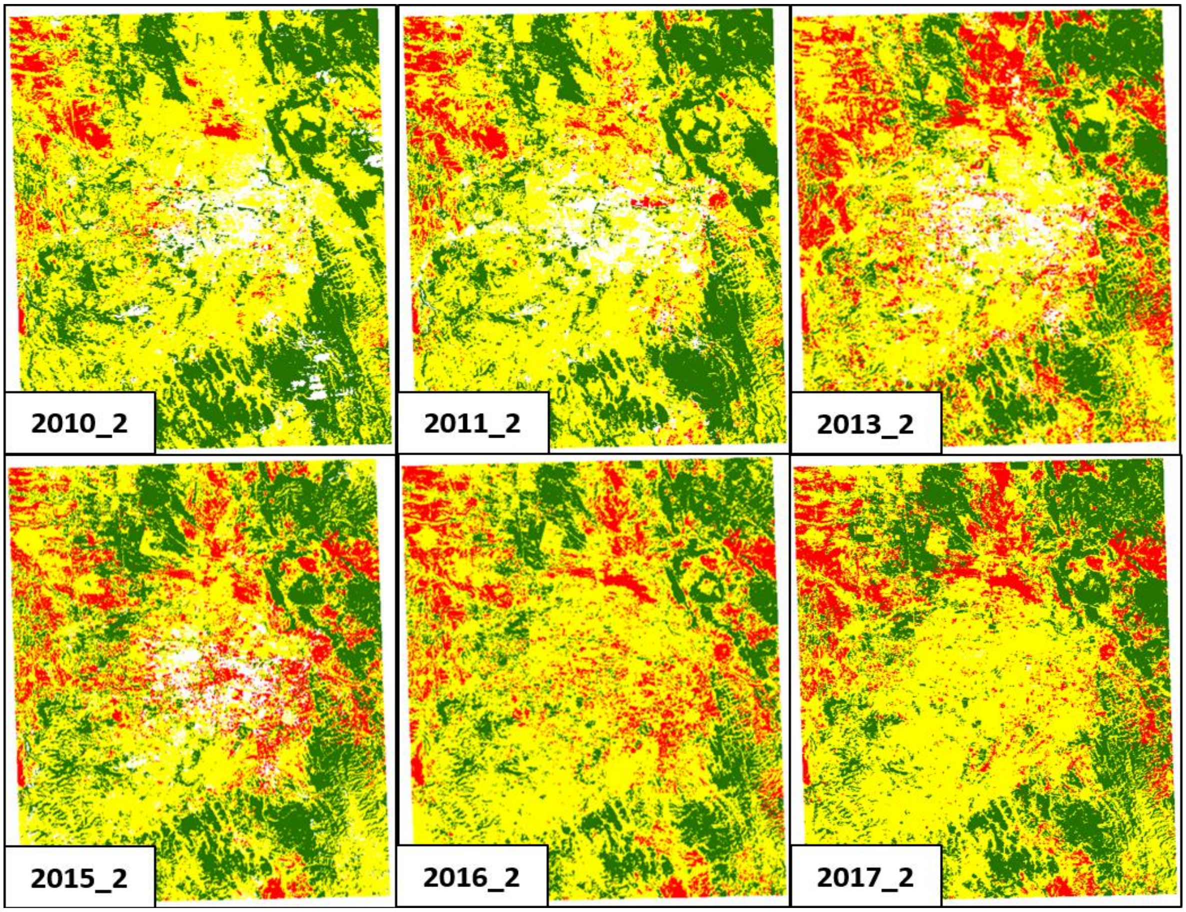
Figure 3. Annual variation in density and distribution of hotspots, detected in EA-4 (adapted from Conabio, 2018).

The number of hotspots varies annually. In regard to their spatial distribution in this study, it was determined that there is a trend in their concentration in certain areas.

In Mexico, fires are recurrently caused by human activities (Pérez-Verdín *et al*., 2013), whose risk and danger can be related to hydrometeorological events (Gutiérrez *et al*., 2015), in which the affected area varies annually. In the study area, during 2011, there was a significant increase in the area affected by fires, which coincides with the situation reported by Gutiérrez *et al*. (2015), who cite an increase in size of the area affected by fires in the State of Mexico in the same year. These fires are associated with the detection of hotspots. In this regard, a trend in the concentration of hotspots in certain areas was observed in the present study, as in those by Zúñiga-Vásquez *et al.* (2017) and Ávila-Flores *et al.* (2010), when spatially modeling forest fires in Mexico and the state of *Durango*, respectively.

The present research evidences, though with some variations, the existence of certain patterns in the location of hotspots, similarly to what Pompa and Hernández (2012) report for the state of *Durango*.

Regarding the spatial variation of the land cover (Figure 4), in general, forest areas remained relatively constant, while grasslands (for use by livestock) showed the greatest variation. This was the case in assessment area 1 (EA-1), which recorded a slight increase in grassland areas in 2015, while EA-2 (Figure 4) exhibited a slight but steady increase in agricultural areas. However, it is important to note that, in some cases, the areas with grasslands have increased significantly from one year to the next. Thus, when comparing between the years 2011 and 2013 in EA-3, an increase in the northeast region was obtained. Subsequently, this region showed a tendency to increase agricultural cover. On the other hand, grassland areas in EA-4 were relatively similar between the years 2010 and 2015, as well as during the 2011–2016 period. Although there was a decrease in this cover, due to an increase in agricultural areas, there was also a decrease in the area of grasslands in the EA-4.



Green = Forests; Yellow = Agriculture; Red = Grassland.

Figure 4. Example of time-space variation of land covers in evaluation area 2 (EA-2).

In this regard, the results suggest that the increase in hotspots is related to the expansion of agricultural and livestock areas; moreover, the correspondence is better defined with the inclusion of the variables referring to livestock (pasture) and forest areas in multivariate models, which could be associated with the occurrence of droughts (Núñez-López *et al*., 2007).

As for the dynamics of the areas by land cover, the graphs of the relationships between the areas and the land cover show that the surface areas remained relatively constant (Figure 5); in particular, the forest cover, although there was a decrease in the areas of EA-3 and EA-5 (Figure 5). In general, the agricultural areas grew in size, although in the case of EA-4 there was a slight decrease. A slight reduction was observed in the pasture areas in those cases in which agricultural areas increased.

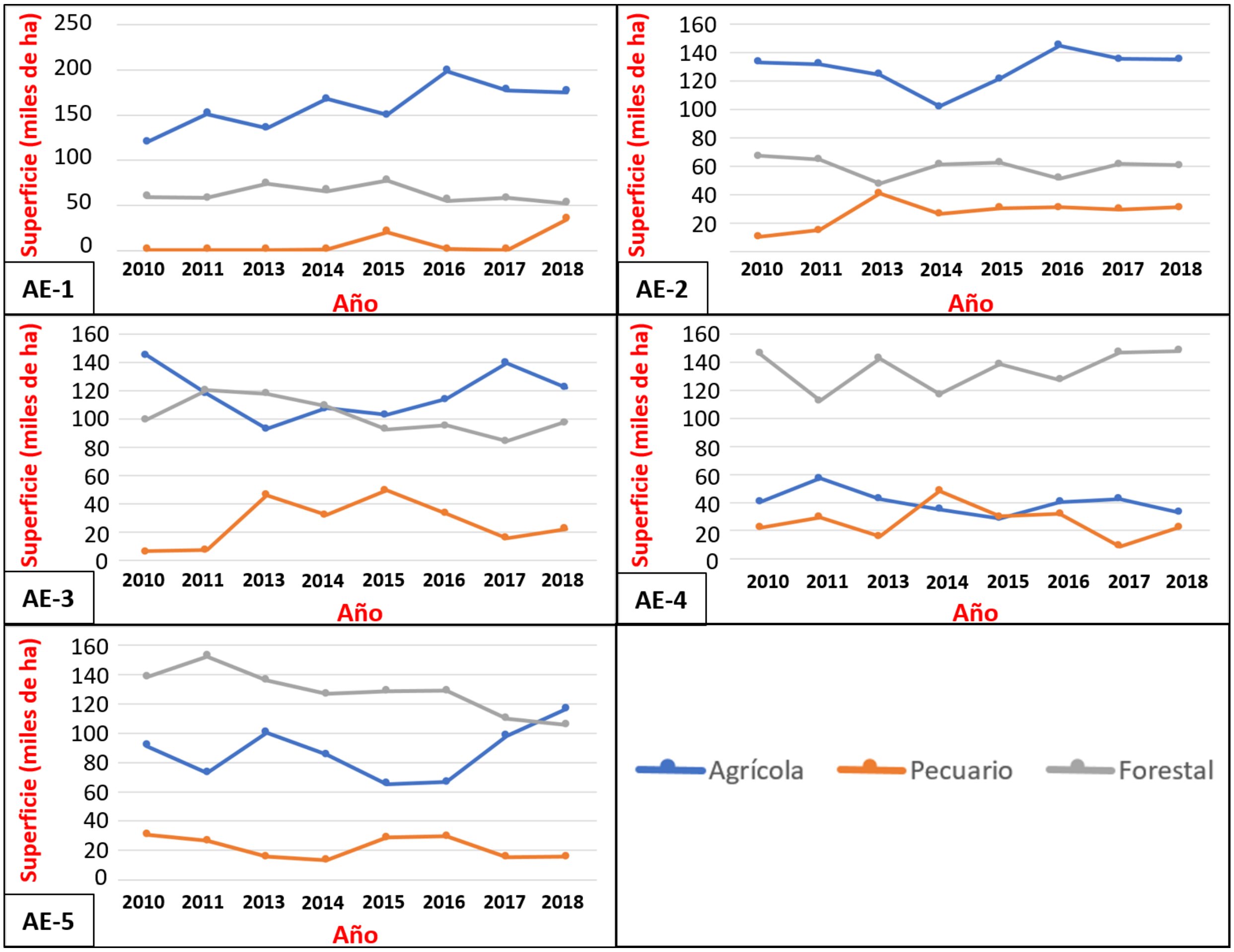


Figure 5. Trends in the area dynamics of forest, agricultural and livestock (pasture) land cover, by EA.

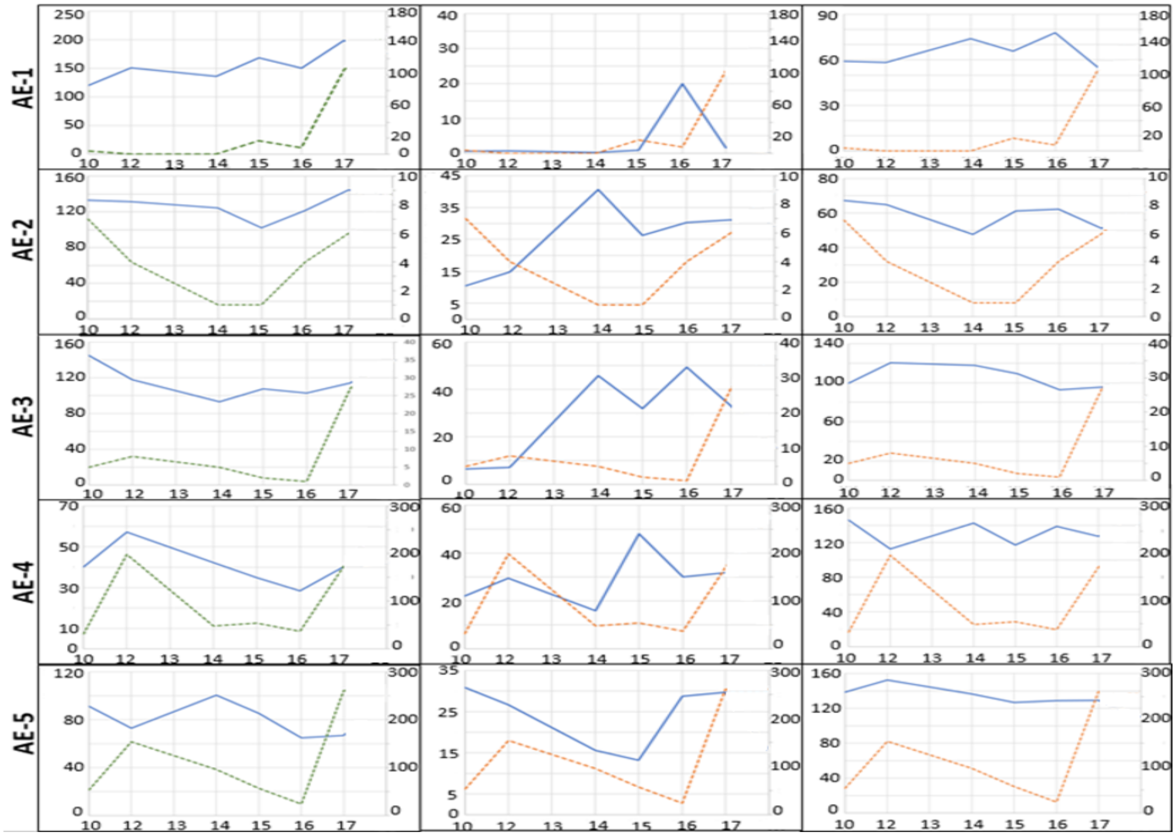
Table 2 shows the dynamics of the analyzed coverage.

Table 2. Total annual dynamics of forests and agricultural and pasture land (in hectares).

Categories	2010	2014	2018
Agriculture	530 054.74	498 003.05	582 480.90
Forest	510 638.68	480 186.81	464 672.19
Pasture	70 448.93	120 304.74	125 689.66

In the evaluated areas, forests have been reported to decrease as those related to anthropogenic activities (livestock and agriculture) increase. This agrees with the data cited by Gordillo-Ruiz and Castillo-Santiago (2017) in their analysis of land use change in the *Sabinal* River basin, in the state of *Chiapas*, as well as with those documented by Escandón *et al*. (2018), who studied land cover and land use change in the state of *Morelos*, using supervised classification in Landsat images. In particular, in some areas there was evidence of a decrease in livestock areas and an increase in agricultural areas, consistently with the findings of Ramos-Reyes *et al.* (2016), who conducted an analysis of land use change in *Comalcalco,* at the state of *Tabasco*.

In general, the analysis of the temporal variations of the agricultural area and HS showed that they are similar (Figure 6). This implies that as the agricultural area (AA) increases, the number of HS also increases. However, the proportion of these variations was different among the evaluation areas; for example, in EA-4 there was greater similarity, in contrast to EA-3 and EA-4, where the temporal variation of HS was greater.



Left ordinate axis = Surface area in thousands of hectares; Right ordinate axis= Number of hotspots; Abscissa= Year, where 10= 2010, 12= 2012, 13=2013, 14= 2014, 15= 2015, 16= 2016 and 17= 2017.

Figure 6. Temporal relationship between land cover areas (continuous line) and hotspots (dotted line), corresponding to each of the evaluation areas (EA).

The relationship between livestock areas (LA) and HS varied between evaluation areas. In this respect, a great similarity was observed in EA-5, while in EA-2 the relationship was opposite (as the LA increased, the HS decreased). In EA-4, the similarity was varied: during the first years, there was a great similarity, but later, the opposite occurred. Notably, there was an inverse relationship in 2017; i.e., as the LA decreased, the value of HS increased. In terms of forest area (FA), there was a slight similarity with the trend of HS; likewise, in 2017, the same behavior was observed as in the case of the LAs.

The percentages of variation of HS in relation to the agricultural area (AA) were generally low (R^2) (Table 3). However, with the exception of AA-5, in most of the evaluation areas (EA) a significant effect (F) of the linear relationship between agricultural area (AA) and HS was identified.

Table 3. Models corresponding to the linear correlation of HS with AA, for each EA*.

EA	Equation	R^2	F	Critical value of F
1	PC = 0.0018 SA – 241.84	0.5731459	6.71360423	0.048774081
2	PC = 0.0002 SA – 15.87	0.5295004	5.62700282	0.063783976
3	PC = 0.0003 SA – 27.677	0.2100746	1.32971236	0.300984936
4	PC = 0.0062 SA – 134.12	0.3031113	2.17474675	0.200303440
5	PC = 0.0001 SA + 120.53	0.0002547	0.00127385	0.972909821

Based on the above, the nonlinear model test of the correlation between AA and HS was improved, although only slightly (Table 4).

Table 4. Non-linear models of the correlation of HS with AA, for each of the EAs*.

EA	Model	Equation	R^2
1	Polynomial (2nd order)	$HS = 2E\text{-}08AA^2 - 0.004AA + 212.95$	0.6107
2	Exponential	$HS = 0.0052e^{5E\text{-}05AA}$	0.5948
3	Exponential	$HS = 0.1309e^{3E\text{-}05AA}$	0.2330
4	Potential	$HS = 2E\text{-}10AA^{2.5303}$	0.3564
5	Exponential	$HS = 41.205e^{1E\text{-}05AA}$	0.0279

However, the integration of the AA with grasslands (LA) and forest area (FA) in multivariate models to estimate the HS resulted in a substantial increase in the corresponding coefficients of determination (Table 5).

Table 5. Multivariate models of the correlation of the HS with the independent variables AA, LA and FA, for each EA*.

EA	Equation	R^2	F	Critical value of F
1	HS = -79.5174 + 0.0015AA + 0.0001LA – 0.0019FA	0.6294	1.6986	0.3370
2	HS = -51.5896 + 0.0002AA + 0.0002LA + 0.00043FA	0.8533	5.8177	0.0910
3	HS = 339.1597 – 0.0012AA – 0.0013LA – 0.0015FA	0.5490	1.2175	0.4376
4	HS = 2745.0835 – 0.0082AA – 0.0163LA – 0.0140FA	0.6402	1.7799	0.3237
5	HS = 525.0944 – 0.0002AA + 0.0014LA – 0.0031FA	0.1386	0.1609	0.9161

In all cases, the FA variable was the most significant, with the exception of EA-5 where the probability of it not being significant was 54.3 %. As for the AA and LA, both were significant in AA-1 and AA-1, and conversely were not significant in AA-5. In EA-3, significance was low for both AA and LA, P= 0.44 and P= 0.38, respectively. In EA-4, the significance was low only in the case of AA (P= 0.47).

The R^2 values obtained in this analysis were higher than those reported by Bucini and Lambin (2002), who used multivariate models to determine the impact of fires on vegetation in Central Africa. On the other hand, the values of R^2 behaved similarly to those recorded by Vega-Nieva *et al*. (2018), authors who developed models to predict hotspots, based on the amount of fuels. The authors point out that the values of this indicator are considered good and that the models predict the hotspots satisfactorily with the variables used.

Conclusions

The results suggest the existence of a relationship between the presence of HS and the variation of agricultural, livestock and forest areas in the state of *San Luis Potosí*. The hypothesis is accepted, since, with the exception of EA-2, the amount of HS increased considerably from 2010 to 2018, and so did the agricultural and livestock areas, while a downward trend is observable in the forest cover. Thus, the inclusion of the hotspots associated with agricultural burning in the generation of forest fire danger models is recommended. Also, the occurrence of HS can be predicted based on variations in forest, agricultural and livestock areas. If it is assumed that there is a correlation between the HS and the occurrence of forest fires, the results of the present work can be used to estimate the trend in the number of forest fires. The amounts of HS in the study area vary from year to year, although their spatial distribution is mainly in areas dedicated to agricultural activities, followed by livestock areas (grasslands). It was possible to establish a significant linear correlation between agricultural areas and hotspots; however, this was not constant in all the areas studied. Finally, multivariate analyses result in better modeling of the hot spot trend, since the R^2 values are significant.

Knowledge of the areas of fire concentration would support the regulation of the use of fire, and would even justify the implementation of training programs on alternative strategies to replace these burns.

Conflict of interest

The authors of this paper declare that there is no conflict of interest with the data used and the results obtained in this analysis.

Contribution by author

José Germán Flores-Garnica: data collection, generation of the models, analysis of the results and drafting of the document; Ana Gisela Reyes-Alvarado: analysis of the results and drafting of the document; Oscar Reyes-Cárdenas: processing of the satellite images, drafting of the document, analysis of the results.

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