Article

Influence of climatic parameters on the population fluctuations of the complex Dendroctonus frontalis Zimmerman, 1868 and Dendroctonus mexicanus Hopkins, 1909

Víctor López Gómez[1]

Brenda Torres Huerta[2]

José Francisco Reséndiz Martínez[3*]

Guillermo Sánchez Martínez[4]

Adriana Rosalía Gijón Hernández[3]

[1]Facultad de Ciencias. Universidad Nacional Autónoma de México. México.

[2]Facultad de Estudios Superiores Iztacala. UNAM. México.

[3]Centro Nacional de Investigación Disciplinaria en Conservación y Mejoramiento de Ecosistemas Forestales. INIFAP. México.

[4]Campo Experimental Pabellón. CIR-Norte Centro. INIFAP. México.

[*]Autor por correspondencia: José Francisco Reséndiz Martínez, Correo-e: resendiz.francisco@inifap.gob.mx

Abstract:

Bark beetles are responsible for the loss of forest mass in Mexico as the second most important cause, so knowing the factors that increase the probability of active outbreaks will help make better decisions for their control. The objectives of the present work were to determine the influence of eight climatic parameters on the population fluctuations of *Dendroctonus frontalis* and *Dendroctonus mexicanus* in two municipalities of the *Sierra Gorda* of *Querétaro* state; as well as to design mathematical models of prediction. A ten-month monitoring showed that only six parameters (temperature, precipitation, atmospheric pressure, wind temperature, thermal sensation and temperature / humidity quotient) were related to the number of beetles of both species, which were only recognized just in one municipality, while relative humidity and wind speed had no effect. Thermal sensation and atmospheric pressure influenced the size of populations of *D. frontalis*, while cumulative rainfall did for *D. mexicanus*. It is concluded that there are atmospheric conditions which are associated with the numerical variations of bark beetles, in addition to those that are usually tested (temperature and humidity). The climatic components that explain the most important differences have a particular effect depending on the coleopteran species; finally, the distance of the meteorological station that registers them must be considered when interpreting such relation because it can generate a high uncertainty.

Key words: Temperate forest, bark beetles, aggregation pheromones, predictive models, monitoring, Lindgren traps.

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Introduction

Pests and diseases are an important factor in the preservation of forest ecosystems. In Mexico, the average area with phytosanitary problems was 51 000 ha between 1999 and 2010, and one of the most important causal agents was barking beetles (mainly the *Dendroctonus*, *Ips* and *Xyleborus* genera) with 15 thousand ha infested in annual average (Díaz, 2005; Semarnat, 2012).

However, bark beetles are crucial in regenerating forest systems, since they naturally only attack and kill diseased trees or long-lived individuals, which keeps the forest in a healthy and productive state. Under certain conditions, the life cycles of these insects accelerate, causing populations to increase in size and become pests, leading to loss of large tracts of forest. Pest outbreaks of the *Dendroctonus* genus have intensified in recent years in several Mexican states especially in the north; in 2013 the area affected by these insects surpassed that damaged by forest fires (12 %) (McFarlane and Witson, 2008; Moore *et al.,* Allard, 2009; CCMSS, 2012; Cuellar *et al*., 2012; Durán and Poloni, 2014).

Querétaro is one of the states where high infestations by barkers were recorded, mainly by *Dendroctonus frontalis* Zimmerman, 1868 and *D. mexicanus* Hopkins, 1909. In 2012 a phytosanitary contingency took place in several municipalities that belong to the *Sierra Gorda* Biosphere Reserve, with damage of approximately 71 000 m^3 of wood (Cibrián *et al.,* 2014).

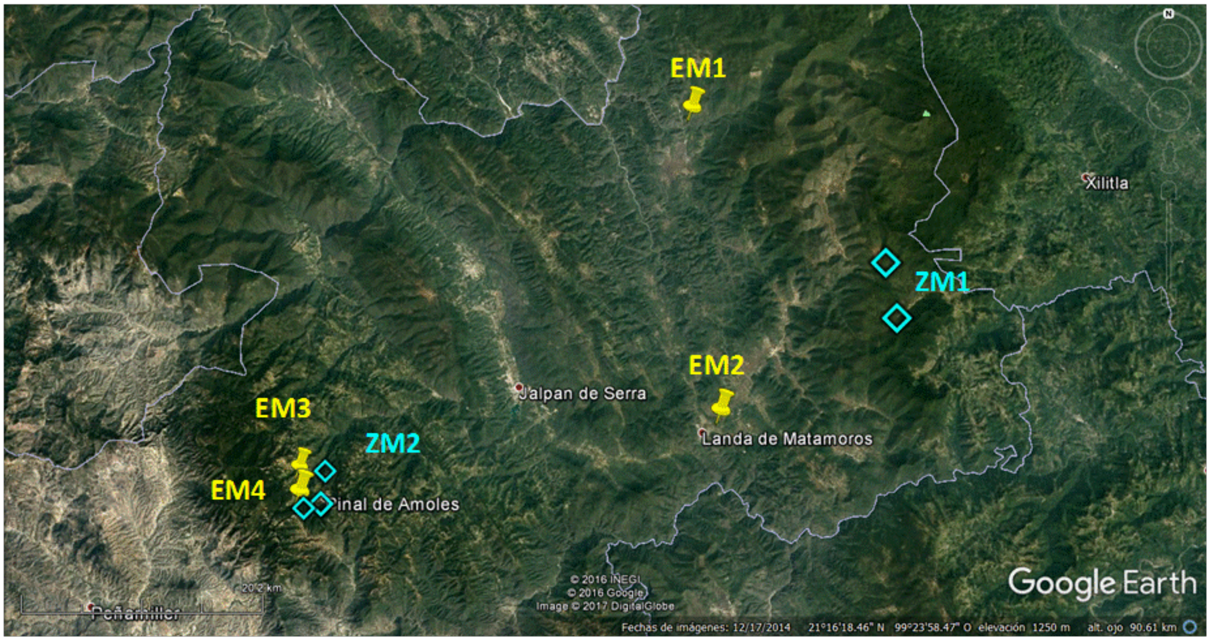
The ecology of bark beetles is complex and dynamic, and in recent years, alternatives for prevention and management have been sought. Some studies have focused on determining the influence of climatological parameters on the increase of their populations in order to generate systems for forecasting epidemic situations, since it has been documented that populations of these barkers are regulated, in part, by the environmental conditions (Flores, 1977; Olivera, 2014).

However, there are currently few records and their results are contrasting, which makes it necessary to strengthen the evidences that show the main trends and to identify the climatic parameters that have a greater influence on the fluctuations of these beetles. In addition, this topic has become more relevant as an increase in the number of generations per year and an in the extent of these species due to climate change has been observed (Moore and Allard, 2009; Rivera *et al.,* 2010; Bentz *et al.,* 2010); thus, a better knowledge of the response of these insects to their abiotic environment will provide the elements to locate the areas of probable risk to the attack of debarkers, to elaborate scenarios and to take the necessary precautions.

Therefore, the objectives of this work were to determine the relation of eight climatic parameters (temperature, humidity, precipitation, atmospheric pressure, wind velocity, wind temperature, thermal sensation and the quotient between temperature and humidity), with *D. frontalis* and *D. mexicanus* on the basis of a 10-month monitoring in two municipalities of the S*ierra Gorda de Querétaro* Biosphere Reserve (*Landa de Matamoros* and *Pinal de Amoles*). It is intended to provide evidence to design predictive models in the future that may help to predict the appearance of active outbreaks for control actions. At present, the models that deal with the problem are very scarce, but there is the work of Cuellar *et al.* (2012) in which they described a mathematical model of this kind.

Materials and Methods

The study was carried out in pine forests of the *Landa de Matamoros* and *Pinal de Amoles* municipalities within the *Sierra Gorda Biosphere Reserve* of *Querétaro*, where *Pinus patula* Schiede ex Schltdl. predominates. & Cham. and *P. greggii* Engelm. Three monitoring sites (i.e., *La Gachupina, Camposanto* and *Tejamanil*), and in *Landa de Matamoros*, two (*Pinalito de la Cruz* and *El Madroño*) (Figure 1) were selected in the municipality of *Pinal de Amoles*. The sites gather pine trees with stems larger than 15 cm of normal diameter and with infestation by bark insects of the *D. mexicanus* and *D. frontalis* complex.



EM1 = *Tancoyol;* EM2 = *Landa de Matamoros*; EM3 = *Pinal de Amoles*; EM4 = *Puerta del Cielo*; ZM1 = *Landa de Matamoros*; ZM2 = *Pinal de Amoles.*

Figure 1. Location of metheorological stations (EM) and monitoring zones (ZM) in *Pinal de Amoles* and *Landa de Matamoros, Querétaro* state municipalities.

At each monitoring site, four 12-cone Lindgren funnel traps were set in which commercial aggregation pheromones (two with frontalin and two with endo-brevicomine) were randomly selected, as well as alpha-pinene for each case (Synergy). In the containers of each trap was placed a plastic strip of 2 cm impregnated with an insecticide of low toxicity composed by Geraniol (2.48 %) and Lavandin (1.86 %), to avoid the escape of the insects and to prevent their predation.

The monitoring consisted of biweekly collections for 10 months (from April 2014 to January 2015) and the baits were replaced every month and a half to maintain its attracting effect. The insects captured in the traps were preserved in 70 % alcohol and then transferred to the *Laboratorio de Sanidad Forestal del Cenid-Comef* (Cenid-

Comef Forest Health Laboratory) (INIFAP), where the *Dendroctonus* genus bark beetles were counted and determined according to their morphology (Wood, 1963; Cibrián *et al.,* 1995) and by the extraction of the seminal rod (Perusquía, 1978; Ríos *et al*., 2008). Only 10 % of the sample was determined when the number of insects exceeded 1 000 individuals. The abundance of *D. frontalis* and *D. mexicanus* was determined for each month from the biweekly records (with the sum of organisms collected from all traps).

The climate information comes from four meteorological stations and was provided by the *Comisión Nacional de Áreas Naturales Protegidas (Conanp) de la Reserva de la Biósfera Sierra Gorda de Querétaro* (National Commission of Protected Natural Areas (Conanp) of the *Sierra Gorda de Querétaro* Biosphere Reserve) (with records every 30 minutes) and from the *Centro de Investigaciones del Agua Querétaro* (CIAQ) of the *Universidad Autónoma de Querétaro* (*Querétaro* Water Research Center (CIAQ) of the Autonomous University of *Querétaro*) (with data per minute). The parameters that were taken into account were temperature, humidity, precipitation, atmospheric pressure, wind speed, wind temperature, thermal sensation, and the ratio of temperature to humidity (T / H); from each of one the average per month was determined, while the temperature / humidity quotient was calculated from the monthly averages. It should be noted that, due to technical failures of the meteorological stations, the complete data were not available, and therefore, the number of days per month varied between 8 and 31 (Table 1).

This study included the largest possible number of atmospheric components, as they provide a more complete picture of the prevailing conditions. Thus, it is feasible to test the possible relationships between poorly used parameters and populations of bark beetles, since most of the works of this nature only handle temperature and humidity.

Table 1. Available months and days of the records from the metheorological stations of the *Reserva de la Biósfera de la Sierra Gorda de Querétaro* (*Sierra Gorda de Querétaro* Biosphere Reserve).

Recorded Months	Range of the recorded days	Institution	Metheorological station (municipality)
May, June, July, October, November and December 2014 and January 2015	10-31	Conanp	*Puerta del Cielo* (*Pinal de Amoles*)
April, August and September 2014	9-31	CIAQ	*Poblado de Pinal de Amoles* (*Pinal de Amoles*)
June, July, August, September and December 2014	12-28	Conanp	*Tancoyol* (*Landa de Matamoros*)
April, May, October and November 2014 and January 2015	8-18	CIAQ	*Poblado de Landa de Matamoros* (*Landa de Matamoros*)

Beetle records of the localities of the municipality of *Landa de Matamoros* were associated with the meteorological stations of *Tancoyol* and the town of *Landa de Matamoros*, while the data of the localities of *Pinal de Amoles* were linked to the stations of *Puerta del Cielo* and the town of *Pinal de Amoles.*

Spearman correlation tests were performed for each municipality in order to determine the relationship between the abundances of *D. frontalis* and D*. mexicanus* with the eight climatic parameters of each month. A non-parametric test was used because the data did not have a normal distribution (Figure 2).

Subsequently, linear regression analyzes were performed (with a significance ANOVA test) only when correlations were significant ($P < 0.05$). For each case, the data were transformed with the base 10 logarithm to obtain the different mathematical models (linear, logarithmic, exponential and potential). The best fit was determined from the coefficient of determination (R^2) and the mathematical models with least squares technique.

Results

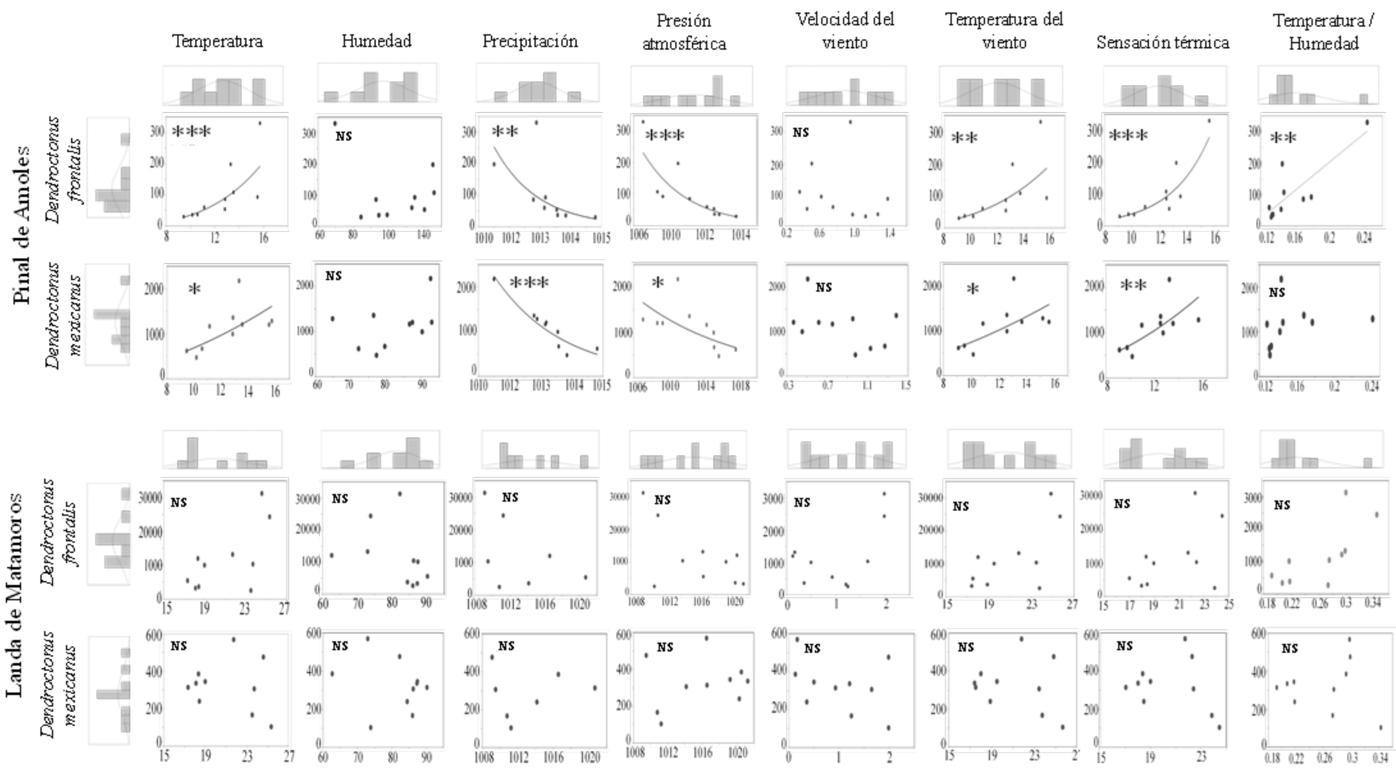
A total of 136 409 bark beetles were catched in both municipalities, from which 121 841 were *D. frontalis* and 14 568 *D. mexicanus* (Table 2).

In regard to the records of *Pinal de Amoles*, positive and significant correlations were found between temperature, wind temperature thermal sensation and T/H quotient with the abundance of both of the barking beetles (*D. frontalis* and *D. mexicanus*), as well as negative and significant with precipitation and atmospheric (figures 2 and 3). On the other hand, there were no significant relations between the abundance of the two species and two of the climatic parameters (humidity and wind speed).

Table 2. Number of individuals of each barking beetle species collected in the two municipalities of the *Reserva de la Biósfera de la Sierra Gorda de Querétaro (Sierra Gorda de Querétaro* Biosphere Reserve).

Municipality	**Species**	
	Dendroctonus frontalis	*Dendroctonus mexicanus*
Pinal de Amoles	956	11 326
Landa de Matamoros	120 885	3 242

From the significant regressions, the best mathematical models between the number of barking beetles and the climatic parameters were mainly of the potential and exponential type. For the first, it was verified between the temperature and the wind temperature for both species and the thermal sensation for the number of *D. mexicanus.* The exponential model was confirmed for both pest species when it was related to atmospheric pressure and precipitation, and only between the thermal sensation and the abundance of *D. frontalis*. Likewise, a single significant linear model was obtained between the registered *D. frontalis* individuals and the T / H ratio (Table 3). On the other hand, data from the *Landa de Matamoros* municipality did not show significant correlations of climatic parameters with both barking species (Figure 2 and Table 4).



NS = Non-significant, * = < 0.05; ** = < 0.01; *** = < 0.001.

Figure 2. Correlations between the abundance of the *Dendroctonus frontalis* Zimmerman, 1868, *Dendroctonus mexicanus* Hopkins, 1909 complex and eight climatic parameters of *Pinal de Amoles* and *Landa de Matamoros* municipalities in the *Sierra Gorda de Querétaro* Biosphere Reserve.

Table 3. Results of the correlations between the abundance of the *Dendroctonus frontalis* Zimmerman, 1868 and *Dendroctonus mexicanus* Hopkins, 1909 complex and eight climatic parameters of *Pinal de Amoles* municipality, *Sierra Gorda de Querétaro* Biosphere Reserve.

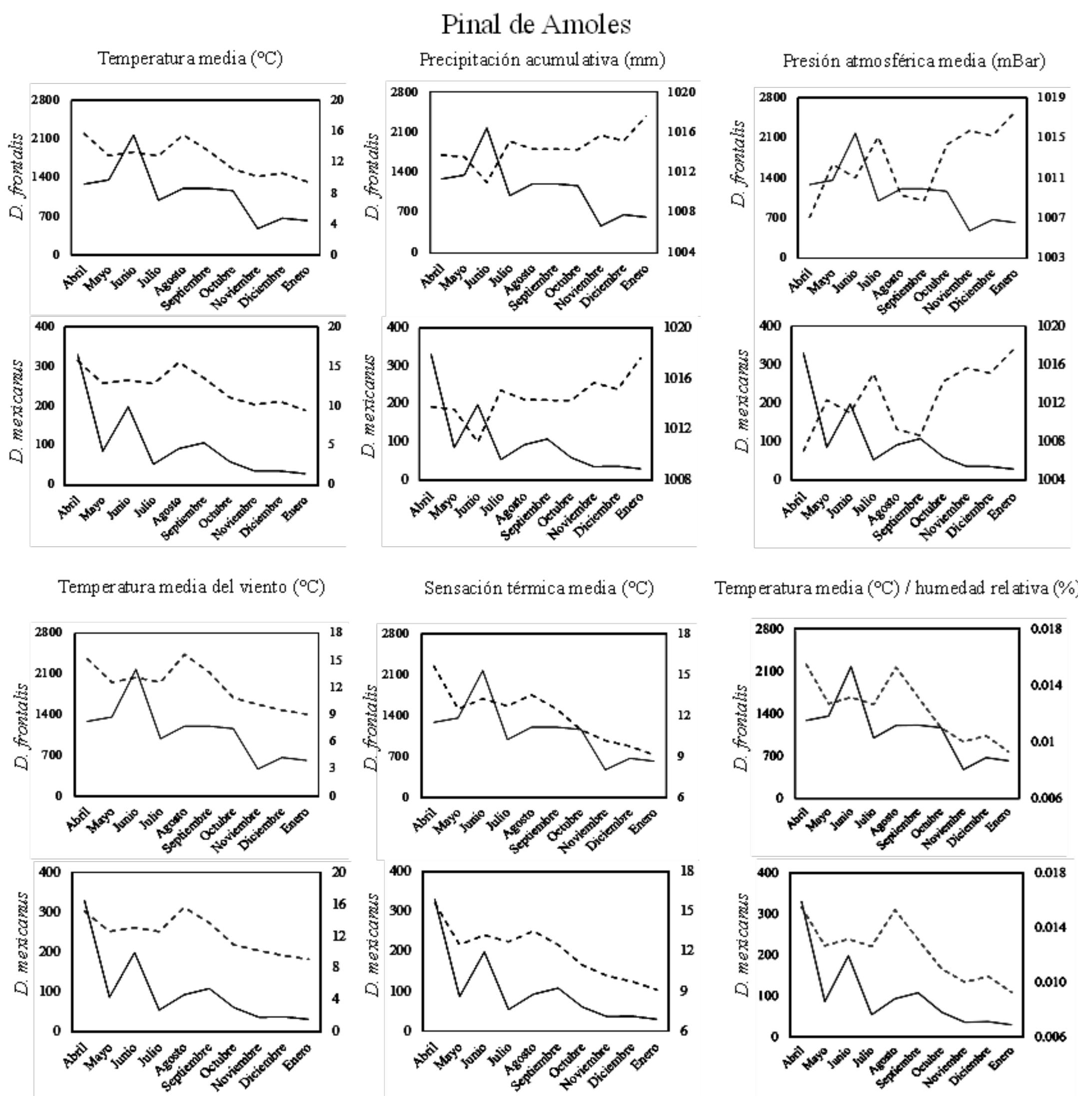
Climatic parametrer	*Dendroctonus frontalis*				*Dendroctonus mexicanus*			
	r_s /*F**	*P*	r_s^2 / r^2	Mathematical model	r_s /*F**	*P*	r_s^2 / r^2	Mathematical model
Mean temperature (°C)	0.94 / 20.82	< 0.001*	/ 0.72	Potential $y = 0.006\ x^{3.7869}$	9.12 / 9.12	<0.01*	/ 0.53	Potential $y = 9.053x^{1.8817}$
Mean wind temperature (°C)	0.87 / 17.46	0.001*	/ 0.68	Potential $y = 0.0173\ x^{3.3748}$	8.62 / 8.62	0.03*	/ 0.51	Potential $y = 14.952x^{1.6982}$
Mean thermal sensation (°C)	0.84/ 42.35	< 0.01*	/ 0.84	Exponential $y = 1.090\ e^{0.3545x}$	10.8 / 10.8	0.01*	/ 0.57	Potential $y = 6.989x^{2.0164}$
Mean atmospheric pressure (mBar)	-0.96 / 42.35	< 0.001*	/ 0.85	Exponential $y=1 \times 10^{89}\ e^{-0.199x}$	6.82 / 6.82	<0.01*	/ 0.48	Exponential $y = 2 \times 10^{41}e^{-0.087x}$
Cumulative precipitation (mm)	-0.88 / 10.53	≤ 0.001*	/ 0.60	Exponential $y =1 \times 10^{157}\ e^{-0.352x}$	22.98 / 22.98	<0.001*	/ 0.77	Exponential $y = 6 \times 10^{104}e^{-0.231x}$
Relative humidity (%)	0.27 /	0.45	0.07 /	NS	0.24 /	0.51	0.05 /	NS
Mean wind speed (m/s)	-0.45 /	0.19	0.21 /	NS	-0.23 /	0.48	0.06 /	NS
Temperature mean (°C)/ relative humidity (%)	0.95 / 9.25	< 0.001*	/ 0.73	Potential $y = 1 \times 10^{109}\ x^{3.7924}$	0.81 /9.33	<0.01*	/0.54	Potential $y = 4 \times 10^{6}x^{1.8897}$

*Significance ANOVA was performed only in those significant Spearman correlations. NS = The model is not indicated because the regression was not significant.

Table 4. Results of the correlations between the abundance of the *Dendroctonus frontalis* Zimmerman, 1868 and *Dendroctonus mexicanus* Hopkins, 1909 complex and eight climatic parameters of *Landa de Matamoros* municipality, *Sierra Gorda de Querétaro* Biosphere Reserve.

Climatic parameters	*Dendroctonus frontalis*				*Dendroctonus mexicanus*			
	r_s	*P*	r_s^2	Mathematical model	r_s	*P*	r_s^2	Mathematical model
Mean temperature (°C)	0.60	0.15	0.36	NS	-0.23	0.61	0.05	NS
Mean wind temperature (°C)	0.60	0.15	0.36	NS	-0.26	0.60	0.06	NS
Mean thermal sensation (°C)	0.44	0.323	0.19	NS	-0.42	0.35	0.18	NS
Mean atmospheric pressure (mBar)	-0.55	0.20	0.30	NS	0.14	0.77	0.02	NS
Cumulative precipitation (mm)	-0.47	0.29	0.22	NS	0.09	0.85	0.01	NS
Relative humidity (%)	-0.33	0.47	0.11	NS	-0.09	0.84	0.001	NS
Mean wind speed (m/s)	0.66	0.11	0.43	NS	-0.12	0.80	0.01	NS
Temperature mean (°C)/ relative humidity (%)	0.53	0.21	0.29	NS	0.10	0.77	0.01	NS

NS = The model is not indicated because the regression was not significant.



The dotted line represents the climatic parameter for each case and its units are on the secondary axis of the ordinates.

Figure 3. Records of the *Dendroctonus frontalis* Zimmerman, 1868 and *Dendroctonus mexicanus* Hopkins, 1909 abundances in *Pinal de Amoles* (over a year) and the six climatic parameters of interest.

Discussion

The relationship between six environmental factors (temperature, precipitation, atmospheric pressure, wind temperature, thermal sensation and temperature / humidity quotient) and the abundances of two species of bark beetles of economic and environmental importance were confirmed (*D. frontalis* and *D. mexicanus*). However, it was only in *Pinal de Amoles* that significant correlations and mathematical models were confirmed, since in *Landa de Matamoros* no relation was verified, probably due to the great distance (21.70 ± 2.60 km) between the monitoring sites (*El Madroño* and *Pinalito de la Cruz*) and the meteorological stations (*Landa de Matamoros* and *Tancoyol*); this situation reduces the likelihood that the data will reflect the microclimatic conditions of the plots at the time of sampling. In contrast, the study sites located in the municipality of *Pinal de Amoles* (*La Gachupina, Tejamanil* and *Campo San*to) are located at an average distance of 2.51 km (± 0.93 d.s.) to the meteorological stations of *Puerta del Cielo* and *Pinal de Amoles.*

The direct relationships obtained between the number of debarkers and the temperature-related parameters (mean temperature, mean wind temperature and mean thermal sensation) can be explained by the dependence of insect activities *(i.e,* dispersion, reproduction, development, growth, among others) to the environmental temperature, which influences its poikilothermic metabolism (Logan and Powell, 2001; Bentz *et al*., 2009; Dukes *et al*., 2009). However, in the case of *Dendroctonus,* contrasting results have been observed with the temperature with which a positive (Bentz, 2009; Hebertson and Jerkins, 2008) or non-significant relation has been recorded (Morales *et al.,* 2016), which may be related to remoteness to meteorological stations, and is not specified in the above mentioned works.

The thermal sensation may be a better parameter to project the abundances of both barks (*D. frontalis* and *D. mexicanus*), since it explains a greater variation of the data (R^2 = 0.84 and 0.57) in comparison with the temperature (R^2 = 0.72 and 0.53) (Table 1). It is the result of the relation between the temperature and the wind speed, so it will present high values when the temperature is so and the wind speed low, and *vice versa* (Pasek, 1988). It appears to encompass two parameters that determine insect activity: on the one hand, temperature affects its metabolic rate, while wind velocity affects flight and its dispersion (Glick, 1939); this influence becomes more evident when organisms are as small as barkers (Compton, 2002). However, in this particular study, wind velocity did not explain the abundances of beetles (Table 1).

The inverse relationship between precipitation and abundance of both scolytes can be explained by the possible weakening of trees in their defense strategy, caused by water stress derived from a low precipitation or water availability; it can be reflected in the low resin production and lower capacity of the host to obstruct the entrance orifices and thus stop the infestation of the beetles (Powell and Logan, 2005; Rivera *et al.,* 2010).

Regarding atmospheric pressure, Bennet and Borden (1971) mention that this parameter is associated with unstable weather conditions and may inhibit the dispersion of debarkers. It has been described that this behavior is perceived through beetle receivers (gas bubbles) that detect the short-term fluctuation of the barometric pressure of the environment (Geiger, 1966).

During periods of low pressure and transition in it, the highest wind speeds arise; changes in this sense are involved in the dispersal of the barking beetles, either to continue or to finish the flight (Chapman, 1967).

The T / H ratio was proportionally associated to the abundances of *D. frontalis* and *D. mexicanus* in *Pinal de Amoles* (Figure 1, Table 1) and it explained a variation of the data above 53 %, confirming that it is a good parameter to relate it to the fluctuation of such pests. However, it did not explain a greater variation of the data (R^2) compared to that obtained with temperature for both species of beetles (Table 1), which coincides with the results of Cuellar *et al.* (2012). This suggests that this parameter should be used in future studies for the projection of the population fluctuations of *D. frontalis* and *D. mexicanus*, since this type of index is calculated with two parameters with great influence in the activities and development of the debarkers.

A relationship of bark abundance and atmospheric humidity was not found, consistent with other studies that show that this environmental variable has a low predictive capacity over population fluctuations of beetles (García *et al*., 2012). However, it has been proposed that the development of these insects is more related to subcortical moisture, since barkers are insects that spend most of their life cycle (immature stage) below the host bark (Íñiguez, 1999; Romero *et al.*, 2007; Cuellar *et al*., 2012; Alvarado, 2013).

The mathematical models obtained were mostly exponential and potential (and there was only one linear), which suggests that the increase or decrease in the number of beetles is generally multiplicative as the climatic parameters change, which describes the nature of the relationship between these two types of variables.

From the frequent geographic overlap and coexistence in the same host, it is common to state that *D. frontalis* and *D. mexicanus* have the same ecological requirements (Zúñiga *et al*., 1995; Zúñiga *et al*., 1999; Salinas *et al*., 2004). However, these results show that the atmospheric pressure and the thermal sensation were the most influential parameters upon the population fluctuation of *D. frontalis* (from the R^2 values obtained) (Table 1), while the cumulative precipitation was the factor that mostly affected the abundance of *D. mexicanus.* This suggests that these two species are different in regard to the physiological ideals with the abiotic factors of the environment that are tightly related with their development and success in the colonization of new sites (Zúñiga *et al.*, 1995).

It is worth mentioning that the mathematical models (those significant) are strong for the species of beetles that were studied (*D. frontalis* and *D. mexicanus*) and for the place of study. And if they are tested in other ecosystems, they may vary in their prediction degree, since they show different trophic interactions of different intensity with their predators and preys, as well as not similar abiotic conditions.

This paper is the first intent to know the relation of a great number of climatic parameters in regard to the population fluctuations of bark beetles of commercial and environmental value, as well as to find the mathematical models that will help to make stronger predictions. However, it is necessary to count with greater evidences of this kind to confirm the tendencies, as well as to test them in contrasting conditions.

Conclusions

The climatic parameters are usually temperature and precipitation generally is associated with the population fluctuations of the debarking beetles as their influence over development and dispersal can be observed directly. However, there are other atmospheric conditions (atmospheric pressure, wind temperature thermal sensation and temperature / humidity quotient T/H), that have significant correlations with *D. frontalis* and *D. mexicanus* abundances, and that could explain a greater variation of the abundances of these beetles.

The distance of the meteorological stations with the sampling plots is a factor that must be weighed against the significance of the relations between the climatic parameters with the population fluctuations of *D. frontalis* and *D. mexicanus*, since they reduce the probability of reflecting the microclimate conditions at the time of data collection. Therefore, it is advisable to have meteorological stations near the monitoring site that record the atmospheric conditions of the locality, or, to put portable stations in the place.

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Conflict of interests

The authors declare no conflict of interests.

Contribution by autor

Víctor López Gómez: field work, advice in statistical analysis; Brenda Torres Huerta: field work, office work, taxonomic analysis, data base handling and writing of the manuscript; José Francisco Reséndiz Martínez: field work, office work, and review of the manuscript; Guillermo Sánchez Martínez: experimental design, field work, review and editing of the manuscript; Adriana Rosalía Gijón Hernández: field work, review and editing of the manuscript.