Article

Calculation of degrees days of *Hypothenemus hampei* through satellite images

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Abstract

Coffee is one of the most relevant crops in Mexico, its importance lies in the fact that it is a sustainable crop, it has been adopted and adapted by indigenous communities and generates foreign exchange for the country. One of the most important coffee growing regions in the country is the South Pacific, made up of Chiapas, Oaxaca and Guerrero where 53% of the coffee is produced and 60% of the producers of this aromatic are found. The presence of pests and diseases in coffee can generate losses between 30 to 50% of production. The *Hypothenemus hampei* (Ferrari) coffee berry borer is the most serious entomological problem of this crop and its presence in the country is over 40 years old, currently it is found in all states that grow coffee. That is why, in this work, a practical methodology was generated that spatially calculated the degrees days of development of the coffee berry borer through the surface temperature recorded by Modis images with a spatial resolution of 1 km and with a one-day temporary resolution, monitoring from April 01, 2018 to March 31, 2019. The results indicated that up to 13 generations of the pest could form in this region, presenting risk almost all year round, both due to development and pest spread. This methodology can help strengthen the monitoring of the pest in the country.

Keywords: coffee berry borer, degrees days of development, heat units, monitoring, risk.

Reception date: February 2020
Acceptance date: May 2020

Introduction

Coffee is one of the most relevant crops in Mexico, its production amounts to more than 800 thousand tons per year and is grown in 483 municipalities in 14 states of the country with an extension of 712 thousand hectares, which represents 3.3% of the agricultural area of the country (SIAP, 2018). 18% of production is exported to 35 countries, contributing 1.6% of the world total produced, generating more than 900 million pesos in foreign currency for the country (SIAVI, 2018).

The cultivation has been adopted and adapted, in its majority, by indigenous communities (> 60%) with native agroforestry systems (Barrera *et al*., 2004), which have been displaced as a consequence of the diversification of production systems associated with the pressures of the world market and together with problems of climate change and the presence of pests and diseases, coffee farming suffers a degradation from all perspectives, noting in the production obtained (-3.9% reduction annually in the last 20 years) and its competition international (Haggar *et al*., 2013; Covaleda *et al*., 2014; Higuera and Rivera, 2018).

Pests and diseases are one of the most important threats to cultivation, and are among the most important limiting factors in the productivity of agroforestry systems, since they can be responsible for the loss of between 30 to 50% of production (Oerke, 2006; Barrera, 2007). Coffee is susceptible to more than 287 pathogens (CABI, 2018) where the most harmful are rust (*Hemileia Vastatrix*) and coffee berry borer (*Hypothenemus hampei*) (Giraldo-Jaramillo *et al*., 2018; Libert and Paz, 2018).

The *Hypothenemus hampie* (Ferrari) coffee berry borer is the main entomological problem of coffee, since it generates low profitability in cultivation, decreases the quantity in production, increases production costs and alters the safety of the drink due to the presence of ochratoxins (Camilo *et al*., 2003; Romero *et al*., 2007). In Mexico, the coffee berry borer was detected for the first time in 1978, in the Mixcum common, Cacahoatan municipality, in the Soconusco Chiapas region, it remained in that site until 1989.

It was reported in San Miguel del Puerto, Pochutla, Oaxaca; in 1991 in Tezonapa, Veracruz and in 1993 came to Atoyac de Alvárez, Guerrero. By 1994 it was present in 97 municipalities in 5 states: Veracruz, Puebla, Chiapas, Oaxaca and Guerrero. In 1998, it came to San Luis Potosí which is the northern boundary areas of the country coffee (Barrera, 2005; Ramírez *et al*., 2007). Currently, the coffee bean is found in all coffee producing areas in Mexico, although infestation levels, determined by agroecological conditions and agronomic management, range from 0 to 8.2% (SENASICA, 2018).

Since the first detection, actions have been carried out in the country to detect and control the coffee berry borer, first the implementation of the integrated management of the borer (MIB) through legal, cultural and biological control, later the publication of the Standard Mexican Official NOM-002-Fito-1995 that established the confinement and eradication of outbreaks of infestation as mandatory, and currently NOM-002-FITO-2000 that establishes all the aforementioned measures, controlling infestations below the economic threshold (<3% infestation) (DOF, 2001; SENASICA, 2016).

Given the social and economic importance of coffee and the environmental and economic damage caused by the spread of *Hypothenemus hampie*, efforts have been made in the country to combat this and other coffee tree pests. An example of this is the creation of the coffee plant phytosanitary epidemiological surveillance program (http://www.royacafe.lanref.org.mx/) and the comprehensive reference system for phytosanitary epidemiological surveillance (https://prod.senasica.gob.mx/SIRVEF/Default.aspx#divVEF) both from the general direction of plant health of SENASICA, where technological tools such as the Smartphone are used to capture data, a web platform for multi-scale analysis and the installation of climate sensors for monitoring and through algorithms that allow knowing the spatio-temporal behavior, models for monitoring and sampling are generated, implemented in the regional control areas (ARCO) (CNRF-VEFCC, 2018).

However, within the monitoring strategies of the Coffee berry borer, it has been necessary to incorporate remote sensing tools. Chemura and Mutanga (2017); Decoro *et al*. (2017), mention that, due to the agricultural complexity and heterogeneity of the crop, satellite images are useful inputs to spatially analyze production and phytosanitary problems of coffee.

Chemura and Mutanga (2017); Cordero and Sader (2007) used Landsat 8 OLI and ETM + images, respectively, the first to classify the coffee crop by age and relate it to production and the second to differentiate coffee from other crops; through standardized indices, both using infrared bands and radiometric resolution to classify and separate coffee from shade vegetation.

On the other hand, Bernardes *et al*. (2012); Brunsell *et al*. (2009) used Modis satellite images to calculate coffee yield using vegetation indices, and despite having low spatial resolution, the high temporality of these images strengthened the phenological analysis of the crop. Hassan *et al*. (2007); Zhang *et al*. (2013) used Modis images to calculate degrees of development days with high levels of precision, and Decoro *et al*. (2017) used high-resolution images to calculate heat units that helped identify areas of risk to nematodes in coffee.

The objective of this work is to develop a practical methodology that spatially calculates the degree days of development of *Hypothenemus hampei* through the surface temperature recorded by Modis images in coffee crops of the South Pacific states. This methodology is presented as an option for monitoring the Coffee berry borer on a regional scale, which is also characterized by not being invasive, it is automatable, with immediate results, with a high spatio-temporal dynamics, which can be used for monitoring and pest surveillance.

Materials and methods

The South Pacific coffee region is one of the most productive in the country, where Chiapas, Oaxaca and Guerrero produce 53.9% of the coffee in Mexico, with a yield of 0.92 t ha^{-1} (SIAP, 2018). 60.5% of the country's coffee producers are concentrated in this area (AMECAFE, 2006), the majority of which are indigenous of different ethnicities (Higuera and Rivera, 2018). In the region, coffee crops are observed in the shade and under the sun modalities, with five different systems, predominantly monoculture under shade, and ranging from 600 to 1 600 masl (Barrera *et al*., 2004).

Currently, the coffee berry borer is reported in 244 municipalities in 11 states, generating economic damages equivalent to 100 million pesos (SENASICA, 2019a) (Figure 1). Currently, the coffee berry borer is found in 44 municipalities in Chiapas with infestation levels ranging from 2.2 to 2.6%, Oaxaca reports infestations between 3.9 to 4.7% in 55 municipalities and Guerrero reports infestations of 1.3% in 5 municipalities (SENASICA, 2018).

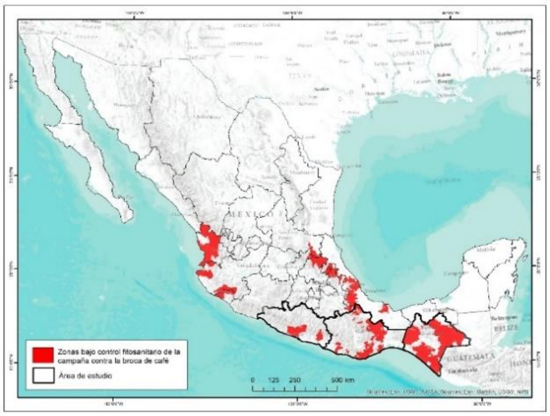

Figure 1. Current situation of the *H. hampei* coffee berry borer in Mexico. SENASICA (2019a).

The degrees days of development (GDD) is an index that calculates the biological development based on temperature and has been applied in the monitoring of crops or insects (Hassan *et al*., 2007). Also known as heat units or development units, the GDD in insects has been used to calculate the development speed based on the lower and upper threshold temperature ranges at which the development of the species ceases and its requirement for accumulation of heat units in order to complete its life cycle (egg-adult) (Maiorano, 2012; Damos, 2015).

For the generation of the degree days model, Modis images were downloaded from the LAADS DAAC platform (https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/Mod11A1--6), specifically the product MOD11A1 version 6 it provides daily Earth Surface Temperature (LST) with a spatial resolution of 1 km by 1 km. 356 images corresponding to a daily one were downloaded from April 01, 2018 to March 31, 2019, and for the total coverage of the states of Guerrero, Oaxaca and Chiapas, two grids were used (H9V7 and H8V7).

The images were processed in ArcGIS v10.7 software, adding the subdataset 0 of each image, which corresponds to the daily LST. Subsequently, the scaling of the pixel values that were originally in a range of 7 500 to 65 535 was performed, this procedure was performed using the raster calculator, multiplying the image by the scale factor that is 0.02, resulting in the pixel value in kelvin unit, which was converted to centigrade (Wan *et al*., 2015). Subsequently, the following formula was applied to each image: $GDD=\frac{Tmin+Tmax}{2} - UI$.

Where Tmin is minimum temperature, Tmax is maximum temperature and *UI* is the lower temperature threshold (Snyder, 1985; Hassan *et al*., 2007). For *Hypothenemus hampei*, the data obtained by Jaramillo *et al*. (2009); Giraldo-Jaramillo *et al*. (2018) who report a minimum temperature and a lower threshold of 13.9 °C and a maximum of 32 °C, with a cumulative degree days of 299 heat units to complete the phases from egg to adult.

For the cartographic representation, a summation of the values per day was made for each month, in addition, a transformation of coordinate systems from the sinusoidal projection to the conic projection was carried out according to Lambert and applied a mask to extract only the pixel values of the study area.

In order to establish relationships between the degrees of days models and the presence and infestation of the pest in the study area, data on the national incidence of captured bitch adults and the averages of brocade fruits and adults captured by site/state. The bulletins used were those corresponding to the months of April 2018 (bulletin no. 56) until March 2019 (bulletin no. 67).

The extracted data were entered into a database and separated by state, in addition to relating them to the municipalities where the pest is reported, so that in turn they were superimposed on the results of degrees days of development obtained from the analysis of the images.

Results and discussion

Derived from the analysis of satellite images, in the South Pacific region there are optimal temperature conditions for the accumulation of degrees days of development of the coffee berry borer. The calculation shows that the scenario is conducive to the development of more than 10 generations of *H. hampei* in a year (Figure 2) and this scenario would only appear if the temperature conditions were constant throughout the year.

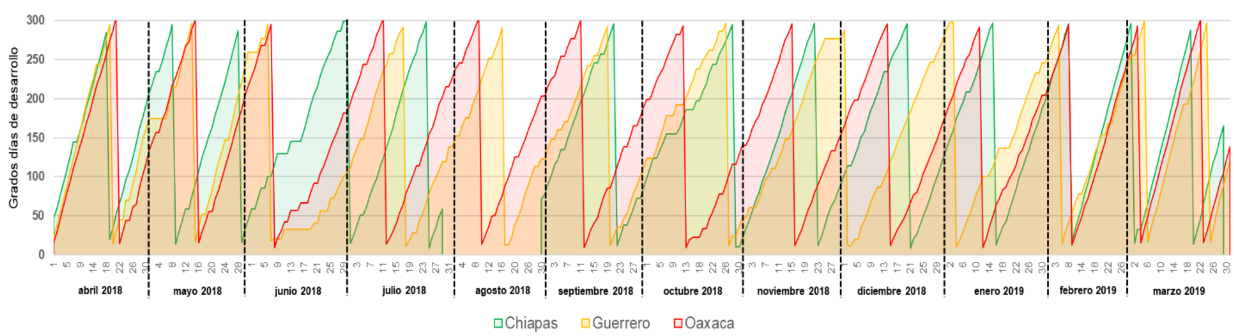

Figure 2. Calculation of degrees days of *Hypothenemus hampei* in Chiapas, Guerrero and Oaxaca, according today, month and year.

Giraldo-Jaramillo *et al*. (2018) mention that the greatest reproduction and incidence occurs when there is an increase in temperature and there is availability of coffee fruit for the infestation, producing annually from 5.1 to 12.4 generations. In Mexico, it has been estimated that with average temperatures of 20 to 22 °C, the generation time is 45 days (maximum 8 generations per year), under field conditions (Ruiz *et al*., 2013). However, the accumulation of the degrees days to complete a generation of the plague is more intense between the months of February to May, with lags between each of the coffee states, reducing the accumulation of heat units between August to December (Figure 2).

It should be noted that coffee in Mexico is produced between the months of October (start of harvest) to May (end of harvest) in the area of Guerrero, Oaxaca and Chiapas (SIAP, 2019). The phenology of the crop varies according to the temperature defined by the season of the year, the altitude and the latitude, while in the months of February and March flowering predominates, from August to December the crop is in a consistent stage and maturing, these being stages with the highest risk for *H. hampei* involvement (SENASICA, 2019b).

The spatial behavior of the degree days of development can be seen in Figure 3, the classification ranges were based on the accumulation of heat units required for each stage of development of the pest (Jaramillo *et al*., 2009; Giraldo-Jaramillo *et al*., 2018). For April and May 2018, the degree days accumulation conditions exceeded 300 heat units, particularly in Atoyac de Alvárez, Coyuca de Benítez, San Luis Acatlán and Malinaltepec in Guerrero, Santiago Nuyoo, Santiago Jamiltepec and Santiago Ixtayutla to the west of Oaxaca and Ocozocoautla de Espinoza in Chiapas, places where there is also the presence of the coffee berry borer.

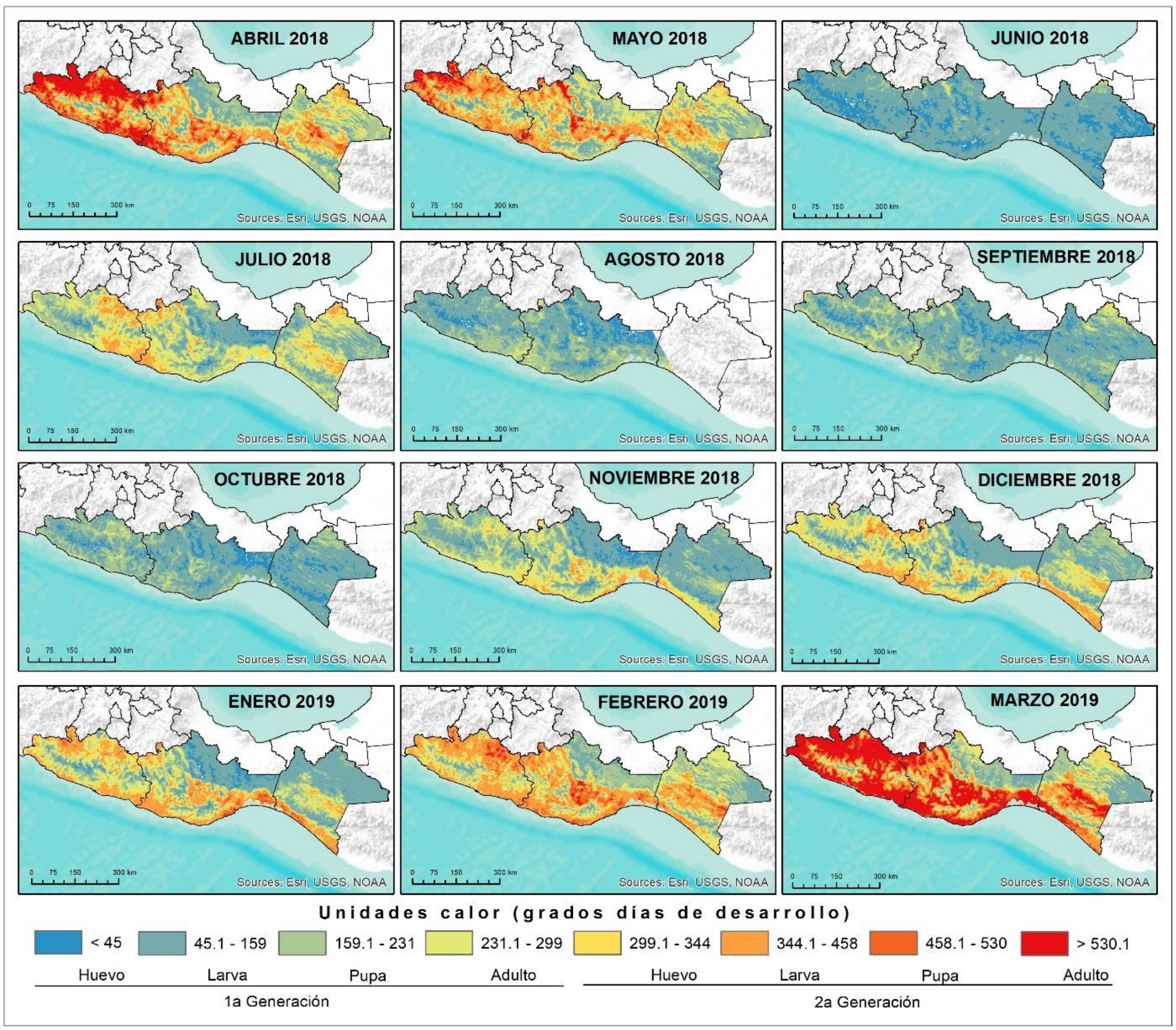

Figure 3. Degrees days of development for the South Pacific region.

According to epidemiological bulletin no. 56 of the month of April (2018) the average catches of adults per site were 76 in Guerrero, 31 in Oaxaca and 152 in Chiapas, while for May (bulletin no. 57) there were 104 catches in Guerrero, 26 in Oaxaca and 67 in Chiapas. It should be noted that, although at this time the cultivation of coffee, its predominant phenological phase was sprouts and fruit tie, it represented a risk due to the number of adults captured. For the month of June 2018, there was a reduction in the degree days of the three states, with accumulations of less than 120 heat units.

Despite the fact that in this month the predominant phenological phase is fruit mooring and milky, the insect tends to abandon the fruit due to its consistency, causing damage to a greater number of grains (Barrera *et al*., 2008). In July 2018, an increase in the degree days was observed and although there were only conditions for the formation of a generation in the municipalities of San Luis Acatlan, Guerrero and Frontera Comalapa and La Concordia in Chiapas.

It represented a risk because in epidemiological bulletin no. 59 the capture of 30 adults on average by state was reported (SENASICA, 2019b), in addition to considering that after harvest, the borer continues to reproduce in the unharvested or residual fruits found in the plant and in the soil (Baker and Barrera, 1993).

From August to October 2018, the accumulation of degrees days did not exceed 200 units, however, the reports of the epidemiological bulletins (bulletin no. 60, 61 and 62) indicate that in these months the highest rates of brocade fruits were presented, with an average of 8.4 fruits per site in Guerrero, 13.7 in Oaxaca and 13.2 in Chiapas. In this period, the phenological phase of coffee was predominantly with consistent fruits, which suggested a high risk of affectation (SENASICA, 2019b).

From November 2018 to March 2019, which is the period when most of the coffee is harvested in the region, the accumulation of heat units increased as the months passed. From November 2018 to January 2019, due to the presence of consistent fruits it generated that risk will be presented mainly in the municipalities of Santa Maria Tonameca, Santa María Ecatepec and Santo Domingo, Tehuantepec in Oaxaca and Pijijiapan, Mapastepec, Mazatan, Tapachula and La Trinidad in Chiapas, with accumulations of degrees days greater than 350 heat units.

In February and March 2019, with the reduction of ripe fruits and the increase of plants in sprouting, the risk was reduced; however, in these months accumulations of heat units greater than 400 heat units occurred in 58% of the municipalities that report the presence of the pest, in addition to the fact that the average adult catch was up to 80 individuals per site (SENASICA, 2019b).

In general, there are two periods in the accumulation of degrees days of development, the one that begins in November and ends in May with temperature conditions that can develop more generations of the pest in reduced periods of time and the corresponding one from June to October where the accumulation of heat units are less, lengthening the development periods of the coffee berry borer.

In the same way, two periods of the *H. hampei* plague are recognized, one in the interharvest period, which runs from May/June to October, where adults go into diapause taking refuge in nuts to resist adverse conditions (Baker *et al*., 1992), while from November to May, there is an emergence of the adult borer, which emerge from the ripe fruits and begin their dispersal flight towards other fruits in bloom (from the new coffee harvest), which gives rise to the first generation of the year (Barrera *et al*., 2006; SENASICA, 2016).

In both cases, the risk to the coffee berry borer is throughout the year, one where it reproduces and the other where it disperses and causes damage to the coffee. This is verified with the data from the epidemiological reports generated from the SENASICA phytosanitary epidemiological surveillance program, where the number of adults caught in traps occurs from January to May and the highest number of brocade fruits occurs from July to October (SENASICA, 2019b). This relationship, mainly with the adults captured in the dispersal period and the degree days of development can be seen in Figure 4.

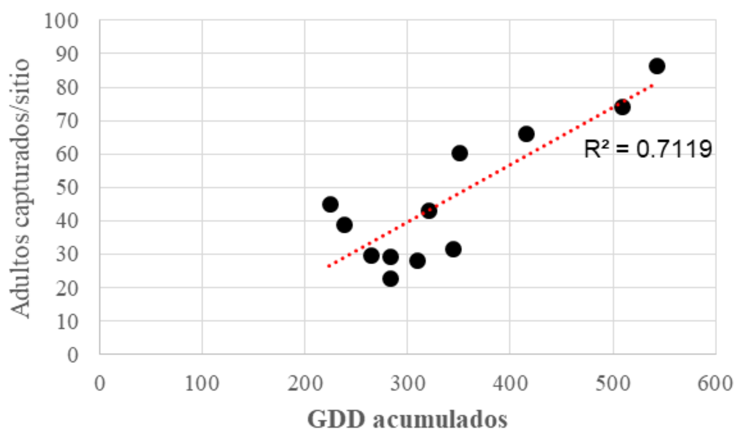

Figure 4. Relationship between the average accumulated GDD and the number of adults captured per site.

When the number of adults captured per site is below 50, the degree days of development do not exceed 350 heat units, and this behavior occurs between the months of June 2018 to January 2019, while the months of April-May 2018 and February-March 2019, the adult catch is greater than 60 and the heat units increase to more than 350 degrees accumulated days of development.

It should be considered in this trend, the source of comparative data, since the results of epidemiological bulletins represent a portion of what is happening in the areas affected by the coffee berry borer, equivalent to 2 890 ha (approximately) monitored from traps, in the three study states, while the results of the heat units are the result of the values of all the coffee areas in each state.

In addition, the spatial resolution of each of these variables is different, while the data for degrees of development days represent an area of 1 km^2 per pixel, the catch data for adults are on average per plot. However, temperature is an important variable for the probability of greater dispersion, reproduction and development of the coffee berry borer.

The GDD data obtained with Modis images represent a continuous spatial coverage, particularly with climatological phenomena. The temperature of the earth's surface is an element that can change according to latitude, altitude, type of vegetation, etc., those changes in the surface can differentiate insect populations. As no data was obtained at ground level for surface temperature, the reliability of the results with respect to heat units can generate uncertainty, in addition to the fact that most studies of heat units use data from meteorological stations and the values are interpolated with different methods.

However, Akther and Hassan (2011) obtained a precision in their GDD classification using MODIS images of 90.3% when compared with data from weather stations. Hassan *et al*. (2007) evidenced that the precision with which GDD classifies MODIS images is greater than 82% reliability. For this study, the GDD data obtained from the images were not compared with data from meteorological stations, due to the absence of digital data, and those that existed were in areas far from the coffee producing areas.

One of the benefits of using Modis images for the calculation of GDD, is the availability of such images, since being a heliosynchronous sensor, it can capture several images in a single day, as well as obtain the resource of the current day (Wan *et al*., 2015). For this study, daily images were downloaded (Mod11A1), although MOD11A2 exists within the MODIS products, which averages the daily images and presents them as weekly average temperature (8 days). In this case, Zhang *et al*. (2013) recommends that for the calculation of GDD, the daily images be used as temporality.

Conclusions

Coffee is one of the most relevant crops in Mexico and the world, it is associated with processes of sustainability, cultural roots and traditional techniques; however, the crop suffers from economic, social, cultural and environmental problems, such is the case that its production has been declining -3.9% annually in the last 20 years. Pests and diseases, associated with climate changes, are problems that impact coffee growing, so creating and applying methodologies that help safeguard the crop are important, especially if these methodologies manage the time variable and its process can be systematized.

The degrees of development days calculated with Modis images are a good input to support the monitoring and surveillance processes of *Hypothenemus hampei* or other pests of quarantine or economic importance. It has been shown that the GDD result for coffee berry borer corresponds to the presence of adults per site, in addition to territorializing the places that have the most suitable temperature conditions for one or more generations of the pest to develop.

In this sense, GDDs with Modis images spatialize the phytosanitary problem, which can be related to some other relevant spatial variable. The images can be used to estimate the monthly and annual number of generations of this pest, for use in integrated pest management programs. According to the calculation, up to 13 generations of *Hypothenemus hampei* can be generated in the South Pacific states. Municipalities with large areas of coffee are at risk in the presence of the most important entomological problem of the crop. This pest can have extraordinary periods of population growth, which could be monitored with these images and through knowing the GDD of the insect.

This methodology can easily be incorporated into the phytosanitary epidemiological surveillance program for the coffee crop.

Acknowledgments

This study was carried out at the Technological Prospecting Laboratory for Innovative Development of Food and Nutrition (PROTEAA) within the framework of the project 'Production and use of coffee. Systemic prospecting of the value chain in the states of Chiapas, Oaxaca and Guerrero' within the call for projects of national problems 2015 CONACYT registered under number 1011.

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