Probability of a Central American locust *Schistocerca piceifrons piceifrons* upsurge in the Yucatan Peninsula, Mexico

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Abstract

From ancient times to the present, infestations of the Central American locust (CAL) [*Schistocerca piceifrons piceifrons* (Walker, 1870)] have occurred periodically and with varying intensities in the Yucatan Peninsula (YP), Mexico. Despite efforts to survey the recession zone, an upsurge is still difficult to predict and prevent, and high economic costs are incurred in controlling this pest. For this study, two models were developed to determine the probability of an upsurge in the YP. The first was the Markov chain (MC) with transition probability matrix, which estimates probability by determining the proportion of times that the system moved from one state to another (n_2) over 71, 33, and 24 years in Yucatan, Campeche, and the Quintana Roo States, respectively, divided into different periods; a correlation of the matrix and probability (n_2) of the next period was performed to evaluate the accuracy of the estimation. The other method is the classic probabilistic (CP) model, which uses the number of times the upsurge could happen and the number of possible events. In the MC model, great variation was found in CAL upsurge probabilities between periods, with a similar number of upsurges from the past to the present but with varying intensity. In recent years, the treated area with insecticides has been less than that of the past. The CP model revealed that the locust population reached its maximum peak every four years, with the migration of swarms to neighboring states at the end/start of the year. Validation of the MC and CP models was performed considering information on areas treated in 2019 and 2020, and good accuracy was obtained. Both models provide information on the probability of an upsurge in the YP. This information can be incorporated into economic models to improve management decisions, such as when to announce early warnings, and to implement preventive control strategies.

Keywords

early warning, forecast, preventive management, recession period

Introduction

Locusts are among the most devastating pests of human agriculture (Lockwood 2015), making them a major threat to global food security and the livelihoods of farmers in numerous countries (Simpson and Sword 2008). *Schistocerca piceifrons* (Walker, 1870) (Orthoptera: Acrididae) is the true locust of tropical America (Harvey 1983). This species has two subspecies: the Central American locust (CAL; *S. piceifrons piceifrons*), known in Mexico and Central America, and the Peruvian locust (*S. piceifrons peruviana*), distributed in Peru and Ecuador (Harvey 1983, Barrientos et al. 1992).

CAL damage has been documented from the Mayan culture and colonial period, which reported drought and hunger as results of this pest (Flores 2011, García 2012), to the present (SENASICA-DGSV 2016). According to Trujillo (1975), a CAL swarm can feed on 30 tons of vegetation per day and, based on its food preference and distribution in 10 Mexican states, the species could affect 5.9 million ha (SENASICA-DGSV 2016).

An important CAL breeding zone is located in the Yucatan Peninsula (YP), Mexico (SENASICA-DGSV 2016), which possesses ecological conditions–such as mainly grass vegetation–for high-density locust development (Poot-Pech et al. 2018). According to SENASICA (2019), the YP receives 50% of the national budget for locust control because of the importance of breeding zones. The YP is located in the southeast of Mexico. It is made up of three states–Yucatan, Campeche, and Quintana Roo–that comprise 181,000 km^2 (9.2% of the national territory). The overall climate is tropical, with strong seasonality and dry (November–May) and rainy (June–October) seasons (Barber et al. 2001). Tropical forest is the dominant vegetation, but grassland is increasing (Durán and García 2010). The soil is heterogeneous and mostly stony (Bautista et al. 2011).

Currently, CAL in Mexico are controlled through government regulations and advice from the International Regional Organization for Plant and Animal Health (OIRSA), an intergovernmental organization founded in 1953. OIRSA was created as a cooperative effort of locust control between Central American countries that are part of the insect's migration path (Barrientos et al. 1992).

Locust plagues occur after a series of events that increase the number of locusts. The series normally begins with a calm period of recession followed by localized outbreaks and upsurges from which a plague may develop and eventually decline (Symmons and Cressman 2001). Locusts survive the dry season as adults and oviposit in bare areas. Young nymphs hatch and feed on adjacent short ephemeral grasses, while older nymphs and young adults survive on taller vegetation (Hunter and Spurgin 1999). An outbreak occurs when multiplication causes a marked increase in locust numbers and densities so that individuals become gregarious and, unless checked, hopper bands and/or swarms are formed (Van Huis et al. 2007). The gregarization process takes several months (Symmons and Cressman 2001). Upsurges are periods after an outbreak that are followed by two or more successive generations of transient-to-gregarious breeding, with populations occupying an expanding breeding area (Van Huis et al. 2007). Periods of one or more years during which upsurges are widespread are considered plagued years (Symmons and Cressman 2001).

The CAL is an old pest in Mexico (Contreras and Galindo 2014) that is still present in breeding areas today. To analyze and forecast the distribution of CAL, Hernández-Zul et al. (2013) built a dynamic simulation to identify suitable conditions for high CAL reproduction rates. Galindo et al. (2014) proposed an early warning system that used multicriteria models and satellite images. Aldama et al. (2014) suggested that outbreak characterization of endemic channels could help in forecasting short-term locust thresholds in zones where outbreaks can occur. The climate, El-Niño Southern Oscillation (ENSO) (Retana 2000, Contreras and Galindo 2014), vegetation, locust density, and predators are additional indicators that could be valuable in predicting a locust outbreak (Henschel 2015).

The strategies for locust control have has recently changed, with attempts focusing on prevention with the use of forecasting tools. Methods for producing Short- and medium-term forecasts have been made indicating potential locust migration and breeding areas (Cressman 1996). Zhang et al. (2019) proposed including monitoring and forecasting as part of current preventive locust management. Presently, biomodels and geographic information systems (GIS) are used to support the monitoring and forecasting of CAL outbreaks (Barrientos et al. 2021), but efficient statistical tools, with or without historical information, are important for the early detection of rapid changes in the breeding and migration of pest species that lead to outbreaks (Naumova and MacNeill 2005). Bayesian statistics and Markov models offer an effective method for long-term population forecasting of pests and can provide locust-control agencies and organizations with the information necessary to implement appropriate management strategies (Xiang-Hui et al. 2010). Knowledge of indirect effects is also a valuable tool for predicting the probability of CAL upsurge, as it is important to be aware of the relationship between areas treated with any pesticide and locust evolution (outbreak, upsurge, or pest) (Prospatin 2012). Van Huis et al. (2007) described the treated areas with any control agent as an answer to the function of locust area and time.

The objective of this research was to develop and compare two models that can produce probability estimates for future upsurges in the YP by analyzing non-weather-related historical CAL data.

Materials and methods

Data acquisition.—To document the occurrence of CAL upsurges, the following sources of historical information on locust were used: Márquez (1963), Trujillo (1975), Pereyra (1991), Chi (2000), newspapers, interviews with locust field officers, and information provided by the National Service of Health, Safety and Agrifood Quality (SENASICA) on the locust control campaign in the YP, Mexico, through its informatics system called the Phytosanitary Campaign System (SICAFI; www.sicafi.gob.mx/DGSV/).

For Yucatan state, CAL data for 71 years (1948–2018) were available (every year had a value). Data for 33 years (1986–2018) were available for Campeche, and 24 years of data (1995–2018) were available for Quintana Roo.

Locust upsurge definition.— Upsurges were used instead of outbreaks because there were two high-density generations–transients-to-gregarious or gregarious-to-gregarious–and migration to other regions (Van Huis et al. 2007); when swarms move beyond breeding areas to other regions, the overall situation exceeds a hazily demarcated threshold from "outbreak" to "upsurge" (Showler 2019). The CAL was present in Yucatan State in a gregarious form in almost years which is reflected in larger treated surface with insecticides (Fig. 1).Upsurges, therefore, allow consideration of the large number of migrant swarms that formed and reached the state of Campeche. As a result of such upsurges, the treated area required for CAL control was high in one year as in 2004, 2006, 2009, 2010, 2014, and 2018 or consecutive years 1952–1955, 1979–1981 and 1986–1989 on gregarious populations (Fig. 1) that reached Campeche during migration. The reaction in this state was the development of highly controlled surface in 2007, 2011, 2015, and 2019 because subsequent swarms (451 in 2006–2007, 245 in 2010–2011, 243 in 2014–2015, and 120 in 2018–2019) migrated from Yucatan (Fig. 2). In contrast, in years without an upsurge, the number of swarms detected in Yucatan was at a minimum (0–60 swarms) and failed to reach Campeche.

Markov chain probabilistic model.—The data were organized by assigning "0" to years with none or low intensity of CAL swarms and "1" to those in which an upsurge occurred. Second, the data were organized into periods of upsurge based on number of years, resulting in 5 periods of 12 years and one of 11 years in Yucatan state; 3 periods of 12 years, except for the first period of 9 years, in Campeche; and 2 periods of 12 years in Quintana Roo.

Classic probabilistic model.—The maximum peak years were obtained using the treated area (ha) in Yucatan state from 2003–2018. Subsequently, a consecutive number was assigned to each of the following years, finalizing in the next peak. A probabilistic analysis of occurrence was performed for each consecutive year. The probability of occurrence in the most recent years (2003–2018) was compared with that of previous periods [1977–1989 (Pereyra 1991) and 1952–1955 (Márquez 1963)].

Model validation.—The probabilistic results of the two models were compared to the results of the treated area in the YP in 2019 and 2020.

Data analysis

Markov chain probabilistic model.—The probability of matrix transition for every period was estimated by determining the proportion of times that the CAL upsurge situation, 0 and 1, moved from one state to another (Kemp 1987). In this context, there were four possible transitions: no upsurge → no upsurge (0→0), no upsurge → upsurge (0→1), upsurge → no upsurge (1→0), and upsurge → upsurge (1→1) (modified from Zimmerman et al. 2004). These estimates were represented by a *p* matrix developed for each year, where

$$p = \left(\begin{matrix} P_{00},P_{01} \\ P_{10},P_{11} \end{matrix} \right.$$

Table 1. Matrix (one-step transition) and n_2, for CAL upsurges in a 71-year period.

Number	Years	Yucatan				Number of years	Upsurge years	Upsurge average	Probability n_2			
		Matrix (One-step transition)										
		0→0	0→1	1→0	1→1				0→0	0→1	1→0	1→1
1	1948–1959	0.5	0.5	0.43	0.57	12	7	1.71	0.46	0.54	0.46	0.53
2	1960–1971	0.5	0.5	0.6	0.4	12	5	2.40	0.55	0.45	0.54	0.46
3	1972–1983	0.71	0.29	0.75	0.25	12	4	3.00	0.72	0.28	0.72	0.28
4	1984–1995	0.2	0.8	0.67	0.33	12	6	2.00	0.57	0.43	0.35	0.65
5	1996–2007	0	1	0.72	0.28	12	7	1.71	0.72	0.28	0.2	0.8
6	2008–2018	0.58	0.42	0.66	0.34	11	4	2.75	0.61	0.39	0.60	0.4
						71 (total)	**33** (total)	**2.15** (mean)				

The elements P_{00} and P_{01} refer to the probability that in X year (present), the following year's CAL population will be classified as low (P_{00}) or high (P_{01}) if X year has low densities. Alternately, if X year has a high locust density, P_{10} is the probability that the following year's populations will be classified as having a low density, and P_{11} is the probability that the state will continue to be classified as having a high density of CAL the next year (Kemp 1987).

The probability of correctly determining the locust density in the next period was obtained using the recursive properties of a two-state Markov chain (Bhat 1972). The matrix P(n−1) was multiplied by the matrix P to generate the matrix p(n). The element-by-element calculations for $P^{(n)}$ were as follows:

$$
\begin{aligned}
P_{00}^{(n)} &= P_{00}^{(n-1)}P_{00} + P_{01}^{(n-1)}P_{10;}\\
P_{01}^{(n)} &= P_{00}^{(n-1)}P_{01}+ P_{01}^{(n-1)})P_{11;}\\
P_{10}^{(n)} &= P_{10}^{(n-1)}P_{00} + P_{11}^{(n-1)}P_{10;}\\
P_{11}^{(n)} &= P_{10}^{(n-1)}P_{01} + P_{11}^{(n-1)}P_{11}
\end{aligned}
$$

The correlation between the probability n_2 of the two-state Markov chain and the probability of the next period (one-step transition)–for example, the probability n_2 of period 1 with the matrix of period 2–was determined using Pearson correlation ($p < 0.05$) in R software version 3.6.0 (R Core Team 2019).

Classic probabilistic model.—We obtained the classic probability using P(1) = #1/M, where P(1) is the probability of an upsurge, #1 is the number of times the upsurge can happen, and #M is the number of possible events (Infante and Zárate 1990). Upsurge years were designated as 1, with years of no upsurge designated as 0.

Results

Markov chain probabilistic model

Yucatan state.—A great deal of variation was found in CAL upsurge probabilities between periods, except in transitions 0→0 and 0→1 of periods 1 and 2. In the first period, transition 1→1 (0.57) was highest, indicating years with contiguous upsurges. The second period was characterized by a reduction in upsurge frequency of 1→1 (0.4). In the third period, this transition had its biggest reduction (0.25), indicating an increase in "recession years," and the transition 0→0 was increased to 0.5 to 0.71 . During periods 4 and 5, the values of the transition matrix were very similar (0→0: 0–0.2, 0→1: 0.8–1, 1→0: 0.67–0.72, and 1→1: 0.28–0.33). Thus, an upsurge appeared in one year, and in the next, it was reduced. The last period was very similar to the second period, where the recession years were increasing 0→0 (0.58) and 1→0 (0.66) and remained high. From 1948 to 2018, there were 33 upsurges at an average of 2.15 per period and with a range of 4 to 7. Periods 1 and 5 had a major upsurge, and periods 3 and 6 had a minor locust presence.

In 4 of 5 cases, the correlation between the matrix and probability n_2 in the next period was negative, and the P-value was not statistically significant ($P > 0.05$). In the period 1972–1983, the correlation was high, positive, and statistically significant ($P \leq 0.01$).

Table 2. Pearson correlation of the matrix and probability n_2 in Yucatan state ($P < 0.05$).

Period	Correlation	P-value
1960–1971	-0.65	0.34
1972–1983	0.98	0.01
1984–1995	-0.26	0.73
1996–2007	-0.75	0.24
2008–2018	-0.64	0.35

Campeche State.—In the matrix, the three periods of CAL upsurge in Campeche State were different. In period 1, which was the shortest, 0→1 (1) and 1→1 (0.72) stood out. Periods 2 and 3 showed identical values–1→0 (1) and 1→1 (0)–and had similar 0→0 (0.57–0.75) and 0→1 values (0.43–0.25).

The number of upsurges per year decreased; the first period had the highest number of upsurges (7), followed by periods 2 (4) and 3 (3).

Table 3. Matrix (one-step transition) and n_2, for CAL upsurges in a 33-year period.

Number	Period	Campeche				Years	Upsurge years	Upsurge overage	Probability n_2			
		Matrix (one-step transition)										
		0→0	0→1	1→0	1→1				0→0	0→1	1→0	1→1
1	1986–1994	0	1	0.28	0.72	9	7	1.29	0.28	0.72	0.2	0.8
2	1995–2006	0.57	0.43	1	0	12	4	3	0.75	0.25	0.57	0.43
3	2007–2018	0.75	0.25	1	0	12	3	4	0.81	0.19	0.75	0.25
						33 (total)	14 (total)	2.3 (mean)				

Table 4. Pearson correlation of the matrix and probability n_2 in Campeche ($P > 0.05$).

Period	Correlation	P-value
1986–1994	-0.88	0.11
1995–2006	0.67	0.32

The Pearson correlation was different in the two periods. In 1986–1994, it was negative, and in 1995–2006, there was a positive association. However, the differences were not statistically significant ($P > 0.05$).

Quintana Roo State.—In the 24 years of data (1995–2018), only one year had a CAL upsurge: 2006. Therefore, the probability for 1→0 and 1→1, equal to 1 and n_2 (Table 5), could not be obtained. According to data from the Quintana Roo Plant Health locust control from Yucatan migrated and caused damage to corn and bean crops and cultivated grasslands and caused defoliation in a nature reserve and on urban trees from August–September. In 2006, locust control operations were undertaken in 1,381 ha.

These swarms were able to oviposit in Quintana Roo and complete the second generation. They also returned to Yucatan at the end of 2006 as swarms. In that generation, 173 ha required control operations. In subsequent years, the locust population was present at a low density in the solitarious phase.

Table 5. Matrix (one-step transition) for CAL upsurges over a 24-year period.

Period	Quintana Roo				Years	Upsurge years	Upsurge average
	Matrix (one-step transition)						
	0→0	0→1	1→0	1→1			
1995–2006	0.9	0.1	0	0	12	1	1
2007–2018	1	0	0	0	12	0	0
Total					24	1	1

Classic probabilistic model

Fig. 1 shows a tendency for upsurges to peak every four years (2006, 2010, 2014, and 2018), except for an additional two peaks in 2004 and 2009, from 2010 to 2018, this tendency was clearer than from 2003 to 2009.Therefore and consequently it was assigned values from years 1 to 4, starting with the maximum peak, e.g: year 2006 (year value 1), 2007 (2), 2008 (3), 2009 (4), 2010 (1), 2011 (2) so on (Table 6); from 1952–1955 and 1977–1989, the tendency of the maximum peaks was less clear, and the treated area was larger than in recent years.

This information was used to identify the upsurge years (Table 6). Then, the probability of an upsurge in the past and current periods was determined (Table 7).

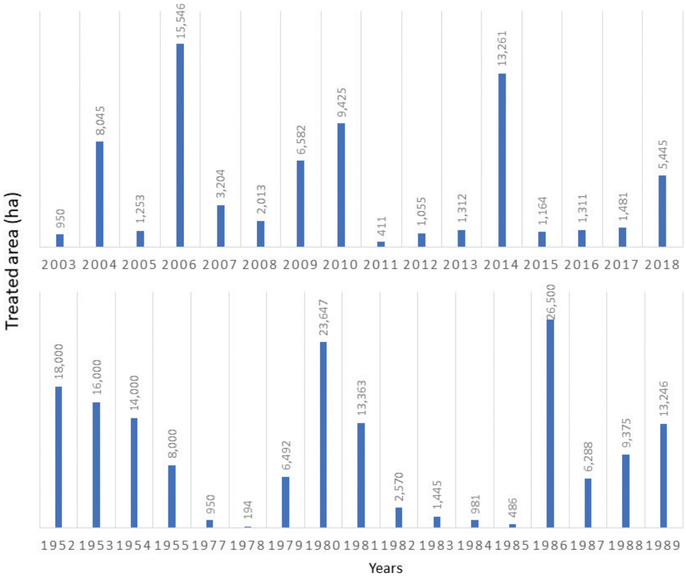

Fig. 1. Treated area in Yucatan State from 2003–2018 (above) and 1952–1955/1977–1989 (below).

For the period 2003–2018 in Yucatan, the highest probability of upsurge was in year 4 (P: 1). There was no probability of an upsurge (P: 0) in year 1 and a minimal probability (P: 0.25) in years 2 and 3. These results were different from the data from the past (1952–1955 and 1977–1988), where years 1 and 2 were similar (P: 0.5) and years 3 and 4 were similar (P: 0.75). For Campeche, the P(1) was 1 in year 1, and years 2–4 had no values. In Quintana Roo, there was only a remote probability of an upsurge, but the probability increased if Yucatan had an upsurge so intense (similar to 2006) that it resulted in locust invasion.

Validation.—According to SENASICA (Table 8), the area treated for locust control was 2,224 ha in 2019 and 3,714 ha in 2020. This information was used to validate the model.

Validation of Markov chain probabilistic model

In Yucatan state starting in 2018, which had a value of 1, the transition 1→0 (one step: 0.66, n_2:0.6) had the highest value. Therefore, the following year, 2019, an upsurge value of 0 would be expected and starting in 2019 as upsurge value 0, the transition (0→0: 0.58, 0.61) was the highest value, so it would also be expected an upsurge value 0 in 2020, both results obtained of the probabilistic model correspond to the results of the low treated area (Table 8). In Campeche in 2018, value = 0, the transition 0→0 (0.75; 0.81) had the highest value, a year with value 0 was expected, but it was not fulfilled, in 2019 according to the treated area the value was 1. The value 1→0 (1, 0.75) was highest for 2020 and

Table 6. Upsurge value for 2003–2018 in the YP and 1952–1955/1977–1989 in Yucatan state.

States	Upsurge value per year															
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Yucatan	0	1	0	1	0	0	1	1	0	0	0	1	0	0	0	1
Campeche	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
Q. Roo	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Yucatan	1952	1953	1954	1955	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	1
Year value	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

it was the upsurge value, through the treated surface (Table 8). In Quintana Roo, despite good results in the probability of 0→0 for 2019 and 2020, no application was made in transition n_2 with an origin of 1 (1→1 or 1→0) because it is an invasion area and not a locust breeding zone.

Validation of Classic probabilistic model

The comparison of the probability of an upsurge P(1), with previous information 2003–2018, with values 2019–2020 indicate that in Yucatan it was according to the model in 2019 and very close to 2020 (P(1)=0.25, value=0), in Campeche and Quintana Roo as predicted.

Table 7. Probability of an upsurge, P(1), from 1952–1955/1977–1988 and 2003–2018.

Year value	1952–1955 and 1977–1988				2003–2018			
	Yucatan				Campeche		Q. Roo	
	Upsurges	P(1)	Upsurges	P(1)	Upsurges	P(1)	Upsurges	P(1)
1	1,0,1,0	0.5	0,0,0,0	0	1,1,1,1	**1**	0,0,0,0	0
2	1,0,0,1	0.5	1,0,0,0	0.25	0,0,0,0	0	0,0,0,0	0
3	1,1,0,1	0.75	0,1,0,0	0.25	0,0,0,0	0	0,0,0,0	0
4	1,1,0,1	0.75	1,1,1,1	**1**	0,0,0,0	0	1,0,0,0	**0.25**

Table 8. Treated area (ha) in the Yucatan Peninsula in 2019 and 2020.

State	Years	
	2019	2020
Yucatan	813	3,420
Campeche	1411	294
Quintana Roo	0	0
Total	2224	3714

Discussion

Markov Chain Model

Yucatan State.—The CAL upsurge from 1948 to 2018 was a sign that the frequency of occurrence had changed, as there were no equal periods. The transition 1→1 had the highest value in the first period (1948–1959); therefore, it was called a "plague period" in which "*favorable breeding conditions are present and control operations fail… two or more regions are affected simultaneously*" (Symmons and Cressman 2001). Upsurge had a higher value in the past than in recent years because there was no organization in charge of a permanent locust control program. Control measures were more recently undertaken over gregarious populations, mainly swarms (Marquez 1963). From 1941–1942, CAL swarms invaded Mexico and Central America,originating from some area of this same region. In 1947, the International Committee for Locust Control (CICLA) was formed; in 1955, the name was changed to OIRSA to include locust surveillance (Marquez 1963, Trujillo 1975). In 1948, the Mexican General Direction of Agricultural Protection was created, an institution that consolidated technical cooperation with CICLA. The first period (1948–1959) in Mexico was characterized by the creation of national and international institutions for locust management (Ortíz and Zuleta 2020).

In the second period (1960–1971), the transition 1→1 decreased, perhaps as an effect of more organized locust control and unfavorable weather conditions, and the number of upsurges per period was reduced from 7 to 5. In period 3, 1972–1983, the transition 0→0 was the highest (0.71). Consequently, because of the fewer number of upsurges (4), the locust was declared to be in its recession period, i.e., a period of several years when the locust population is low (Symmons and Cressman 2001).

In periods 4 (1984–1995) and 5 (1996–2007), the values of the transition matrix were very similar, the transition 0→1 and 1→0 were high, that is the upsurges occurred approximately every 2 years. When starting with a solitarious population, CAL needs three generations to reach the gregarious phase (Barrientos et al. 1992). The CAL presents two generations per year (Astacio 1966, Trujillo 1975); therefore, a third generation is achieved within two years, which concurs with the calculations of Marquez (1963), who indicated that "*the locust does not form suddenly; it takes two or more years to develop.*" In periods 4 and 5, transition 1→1 was reduced because locust management was strengthened with the creation of state-run locust control programs. For example, in 1988, the Ministry of Agriculture and Water Resources of Mexico granted greater autonomy to phytosanitary programs in each state, including the locust control program. The Federal Plant Health Law (Ley Federal de Sanidad Vegetal 1994) created plant health committees to develop multiple crop protection programs with government funding. These programs encompassed the locust control campaign. In Yucatan, such a committee was created in 1997 and is currently responsible for the permanent monitoring and control of this pest.

Although Yucatan periods 1 and 5 had similar upsurge years (7), the severity differed. The overall area treated with insecticides in period 1 (1952–1955) was 56,000 ha (Márquez 1963), while it was 26,363 ha in period 5 (2003–2006), which was 47% less than in the first period.

Only 1 out of 5 correlations between the probability n_2 and the matrix was positive and significant. This may be because the outcome of the Markov chain depends on the outcome of previous events, meaning that the next state of the system depends on the present state, and locust outbreaks are erratic events (Symmons 1992). Showler (2002) outlined broad strategic approaches to locust outbreaks based on intervention timing (prevention or reaction) and tactics (survey, control, economic effects, insecure areas, and contingency planning). Management, weather, climate change [World Meteorological Organization-Food and Agriculture Organization (WMO-FAO) 2016], and political decisions differ in different periods, making it difficult to obtain reliable probability.

Markov models have limitations, are problematic with short time intervals, cannot be derived rigorously from deterministic, dynamic models, and rarely provide the range of time for which the model is appropriate (DelSole 2000). However, they permit knowledge of the outbreak population in each period without the necessity of searching for causation through correlative procedures (Kemp 1987). Weather conditions that could have an influence on outbreaks include the amount of rain in the year (Steinbauer 2011), temperature, relative humidity (Al-Ajlan 2007), wind for migration (WMO-FAO 2016), ENSO (Contreras and Galindo 2014), and precipitation in previous years (Skinner and Child 2000, Chiconela et al. 2003).

In some species of Orthoptera, there has been a decrease in outbreaks; for example, outbreaks of rangeland grasshoppers in Wyoming are highly erratic events, with instances of infestations persisting for multiple years being quite low, so there is little basis for prorating the benefits of control beyond the year of treatment (Zimmerman et al. 2004).

Campeche state.—Historically, the Campeche state has been invaded by swarms from Yucatan (Márquez 1963). The entry and migration routes are found in the north, but these swarms can quickly move to the south of the state (Chi 2000). This movement is made by the second generation and at the beginning of the year (Cullen et al. 2017). In the second period (1995–2006), there was a reduction in the number of upsurges per year, probably because the locust campaign of Yucatan Plant Health established control operations in 1997, reducing the possibility of migration to Campeche. Before this period, the largest number of upsurges occurred, with the transition 1→1 indicating several continuous years with an upsurge or a reduced recession period (0→0). In the third period, there was an increase in the recession period 0→0 because the upsurge was dependent on outbreak and migration from Yucatan every 4 years (2006, 2010, and 2014). The probability of upsurge in 2019 was expected because of the migration of swarms from Yucatan in 2018.

With the information obtained on the control and migration of swarms, it was possible to construct the migration route of CAL to Campeche. At the beginning of the year, Campeche is an invasion zone (Fig. 2) for swarms originating from places in Yucatan, where it is difficult to undertake survey and control operations. Therefore, it is important to carry out locust management tasks in Yucatan state with new methods to reduce migration to Campeche. Despite the large number of swarms formed in Yucatan in the upsurge year, the damage was minimal for two reasons: a) in the maximum period of migration that occurs at the end-beginning of the year, there is less cultivated area, as most of the agriculture occurs in June–September when there is a greater amount of precipitation to help rainfed crops, and b) the size of the swarms, according to the classification of Cressman (2001), corresponds to very small swarms (<1 km^2) due to preventive management of first stage nymphs.

Quintana Roo State.—Vegetation is very important for locust development (Sword et al. 2010). Its distribution (Despland et al. 2000), coverage, and status (green or dry) influence locust gregarization (Cisse et al. 2013). Models could be enhanced by using associations between plant communities and insects to predict risk areas (Van Der Werf et al. 2005). The CAL is highly associated with the grass *Panicum maximum* (Poot-Pech et al. 2018); however, in Quintana Roo, the vegetation is 90% tropical forest, 3.3% agriculture, 3.2% grasses, and 3.5% other uses (INEGI 2011). According to survey information from the locust campaign, *P. maximum* is not the dominant grass in Quintana Roo.

Classic probabilistic model

In Yucatan in 1952–1955 and 1977–1988, there were 10 upsurges and 6 recession years, while in 2003–2018, there were 6 upsurges and 10 recession years. This may be because the structure of the locust program was modernized during the latter period, with greater autonomy and economic resources for developing the program and prevention strategies (Rodríguez 2000). The locust program in Mexico receives technical support from OIRSA (Ortíz and Zuleta 2020), and in general, biological and ecological knowledge about locusts has increased, which has helped create better management practices for this pest (Lecoq 2021).

Periods of 4 years (Table 7) were formed, and a linear regression of areas treated for CAL was obtained (Figs 3, 4), finding a positive relationship. Generally, the first year had the least amount of treated area, and the fourth year had the most amount of treated area. In the fourth year, there was a high migration of swarms to Campeche (Fig. 2), so the gregarious area remained at low infestation for three generations. Two years later, the population became high once again (Márquez 1963, Barrientos et al. 1992). However, this pattern occurs when the swarms are controlled

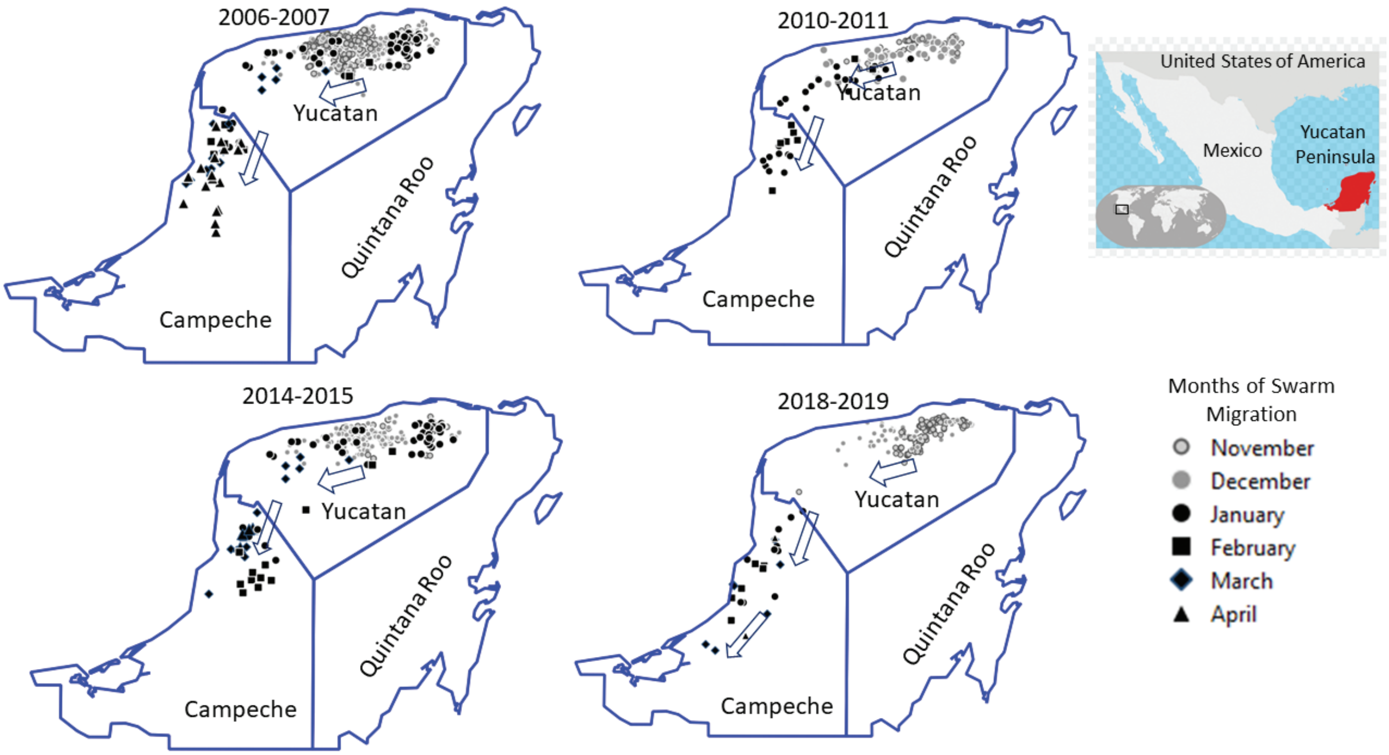

Fig. 2. Swarms detected and treated in the Yucatan Peninsula from November–December (2006, 2010, 2014, and 2018) and January–April (2007, 2011, 2015, and 2019).

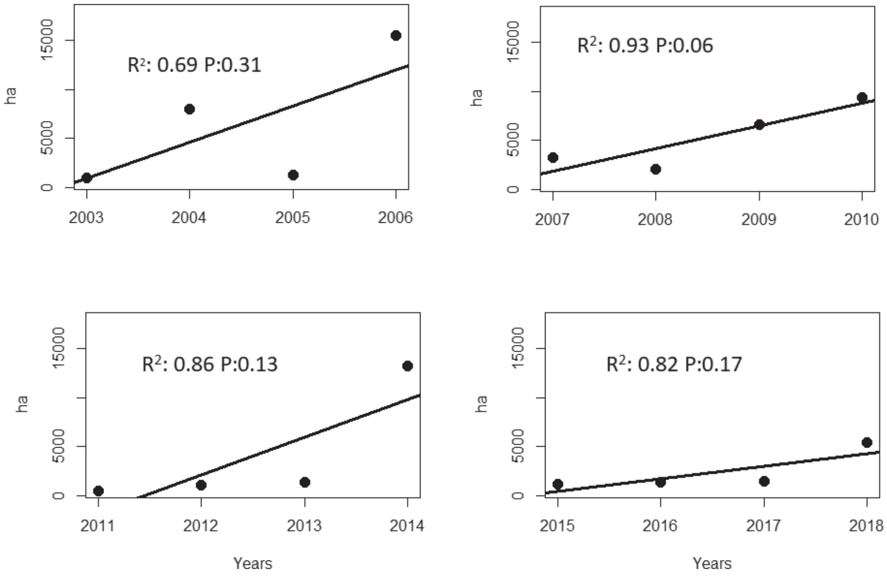

Fig. 3. Linear regression of the treated area in periods of 4 years from 2003–2018 in Yucatán (SENASICA information).

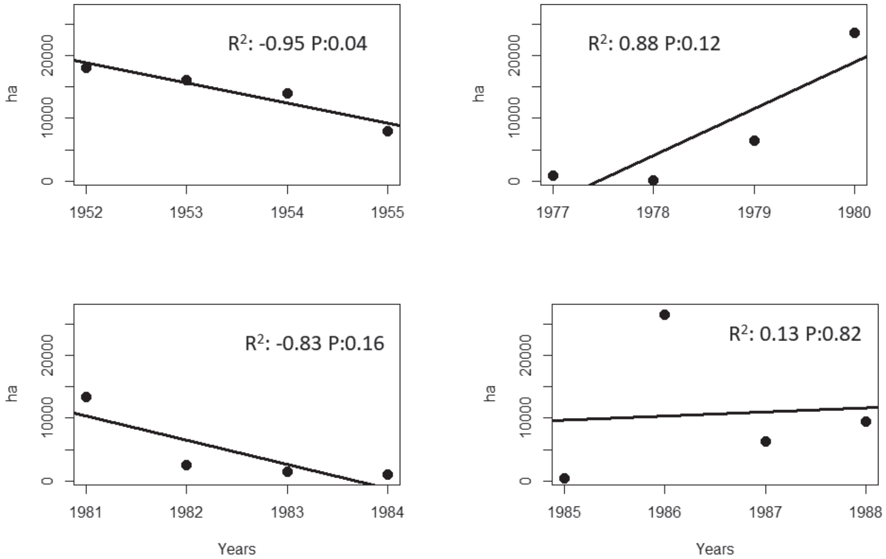

Fig. 4. Linear regression of the treated area in periods of 4 years from 1952–1955 (Marquez 1963) and 1997–1988 (Pereyra 1991) in Yucatán.

along their migration route; if the swarms are not controlled, then year one would have a high infestation when the swarms oviposit and return in the next generation, flying in the opposite direction (Cullen et al. 2017) and repeating the pattern presented in previous periods (1952–1955 and 1977–1988; Tables 6, 7) with at least two years of high infestation. This has been seen recently, such as in the upsurge in 2019 and 2020 of the desert locust in Pakistan (Sultana et al. 2021) and Africa (Peng et al. 2020, Salih et al. 2020).

There were intermediate years–year 2 in 2004 and year 3 in 2009–which were likely the result of suitable weather conditions such as precipitation in the breeding zone. A marked increase in locust numbers on a local scale due to concentration, multiplication, and gregarization can lead to the formation of hopper bands and swarms (Roffey and Popov 1968).

In 1952–1955, there was a "plague" of CAL, requiring 4 years of intense control; gradually, the size of the controlled area was reduced. The opposite situation occurred in 1977–1980 and 2007–2010, with an intermediate rebound in 1979. This situation lasted until 1981, and the treated surface area was reduced until 1984. There was another plague from 1985–1989, with 1986 having the largest controlled area.

From 1952–1955, as shown in Fig. 4, there was a negative regression, indicating a plague of CAL (Symmons and Cressman 2001). Efforts were made to reduce the population each year, but control was aimed at the gregarious phase and mostly swarms (Márquez 1963). International cooperation among countries was still in development (Yam and Zuleta 2020). In 1977–1980, there was a positive regression; an increase in the population occurred in 1979–1980, but in 1981–1984, there was again a negative regression, with a rebound in 1981. Finally, in 1985–1989, the regression value was low because in 1986, there was a higher peak; however, in the period 1986–1987, there was a plague.

In his book, An Account of the Things of Yucatán, written in 1566, Diego de Landa (2003), bishop of Yucatan, wrote about the consequences of locusts and noted the 4-year recession period, saying, "*the locust developed for 5 years, which left no green thing, it was so hungry that people fell dead on the roads* ... with 4 good years after the locust population had improved somewhat."

Table 9. Results of Markov matrix in 2018 compared to results from 2019 and 2020 upsurge values.

State (value year 2018)	Matrix	Values				Upsurge value	
		0→0	0→1	1→0	1→1	2019	2020
Yucatán	One-step transition (2018=1)	**0.58**	0.42	**0.66**	0.34	0	0
	n2	**0.61**	0.39	**0.6**	0.4		
Campeche	One-step transition (2018=0)	**0.75**	0.25	1	0	1	0
	n2	**0.81**	0.19	0.75	0.25		
Q. Roo	One-step transition (2018=0)	1	0	0	0	0	0

Table 10. Probability of an upsurge P (1) and results of upsurge values 2019 and 2020 in the YP.

Year value	Years	Yucatan		Campeche		Q. Roo	
		P (1)	Value	P (1)	Value	P (1)	Value
1	2019	0	0	1	1	0	0
2	2020	0.25	0	0	0	0	0
3		0.25		0		0	
4		1		0		0.25	

Infestation of the desert locust, *S. gregaria*, in Africa occurred in four out of five years between 1860 and 1963, and subsequently, in one year out of six (Symmons 1992). In India, from 1863–1962, there were 10 locust infestations, with 5–6 consecutive years of widespread reproduction, swarm production, and damage to crops, followed by 1–8 years of low activity; from 1963 to 2012, there were 18 upsurges (Sharma 2014).

The WMO-FAO (2016) listed the effects of the following factors on the development of a locust outbreak or upsurge: management; the failure to implement a preventive control strategy; inexperienced field survey teams and campaign organizers; insufficient or inappropriate resources; lack of training of the field officers; inaccessibility to important breeding areas; the weather (precipitation, temperature, and wind); and climate change. These factors are likely to have influenced the high occurrence of CAL in the intermediate years (years 2 or 3).

Additionally, limited financial capacity and ongoing armed conflicts could have rendered some of the locust breeding areas inaccessible, and the coronavirus pandemic lockdown has further hampered control efforts (Salih et al. 2020). Political and socio-economic conditions (Meynard et al. 2020) can also greatly influence the likelihood of locust outbreak by affecting management decisions (Gay et al. 2018). In period 2003–2018 there was an important change of government in 2007 in Yucatan State (https://www.yucatan.gob.mx/?p=cronologia) that included a change in locust-control decision-makers. A clear difference between the periods 2003- 2010 and 2011–2018 can be seen: Four upsurges were present in the first period, with only two in the second. In the second period, upsurges only occurred every four years as a result of the preventive actions and the incorporation of new technologies in the locust-control program (Barrientos et al. 2021).

Plagues arise when locusts breed frequently and successfully over a period of one or more years, with repeated and widespread rains in successive, often widely separated, seasonal breeding areas. This allows swarms to form and invade the agricultural zones surrounding the recession area. Pest control, drought, and migration to unsuitable areas can have an effect on ending plagues, although their relative importance is not always clear (Pedgley 1981). The uncertainty of pest outbreaks and associated damage (risk) can be reduced by preventive practices and by the selective use of pesticides based on monitoring and forecasting (Daamen and Rabbinge 1991). It is very important to predict and identify locust recession periods because these populations begin the invasion when ecological conditions become favorable (Lazar et al. 2016), and early prevention strategies have been proven to prevent damage to major agricultural zones in the invasion area (Sharma 2014). However, the response to an alert must be quick; otherwise, swarms will invade several regions, making the forecast pointless (Ceccato 2007).

Curiously, from 2003–2018, the largest treated area against CAL (Fig. 3) coincided with the years in which a soccer championship was held (2006 Germany, 2010 South Africa, 2014 Brazil and 2018 Russia), so in Yucatan these CAL upsurges are known as "soccer world cup locusts".

Both probabilistic models are functional as long as the permanent monitoring system is sustained and allocated resources are maintained or increased. A reduction in budget would risk the development of the pest, as has occurred in the past. The results of the models discussed here provide insights into the probabilities of CAL upsurges in the YP, and this information can be incorporated into ecological models to improve CAL monitoring and aid management decisions.

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