Area Freedom in Mexico from Mediterranean Fruit Fly (Diptera: Tephritidae): A Review of Over 30 Years of a Successful Containment Program Using an Integrated Area-Wide SIT Approach

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Area freedom in Mexico from Mediterranean fruit fly (Diptera: Tephritidae): a review of over 30 years of a successful containment program using an integrated area-wide SIT approach

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Abstract

The Mediterranean fruit fly (Ceratitis capitata, Wiedemann; Diptera: Tephritidae) is regarded as one of the most destructive insect pests worldwide. It was first detected in Mexico (border with Guatemala) in 1977 after it had spread throughout the Central American region. By 1982, using an area-wide IPM program that included the Sterile Insect Technique, the Moscamed Program, established by the federal governments of Mexico, Guatemala and USA, succeeded in eradicating the pest from the areas it had invaded in Mexico. Recurrent pest entries in the form of transient detections and outbreaks continue to occur in the southern-most States of Mexico bordering Guatemala. The pest free area status is maintained by eradication actions whose effectiveness is verified by an extensive and intense surveillance network including 24,760 traps. In terms of the International Plant Protection Convention (IPPC), the Mediterranean fruit fly pest status can be defined for most of Mexico as “Pest Absent” (i.e., no records of the presence of the pest confirmed by surveys in 28 States of the 32 States) and as “Pest Transient” (i.e., pest entries that do not result in establishment after applying appropriate phytosanitary measures for their eradication) for the southern border States of Chiapas, Tabasco and Campeche, and for the northern border State of Baja California. The very significant investment that the Government of Mexico has made in the Moscamed Program for over 30 years has been extremely cost-effective (benefit-cost ratio of 112 to 1), when compared to the multi-billion dollar horticultural industry that has developed during this period. In addition through the years, the program engaged its own scientists and scientists in a number of countries and organizations in innovation and optimization of important technologies. These include production techniques for an only male genetic sexing strain, emergence towers, aerial release machines, organic targeted insecticide baits, long lasting bait stations, Phase IV traps and female biased attractants, and use of global positioning systems for data analysis and forecasting and for routing aerial releases. These tools have led to increased program effectiveness and have been adopted in many countries.

Key Words: Ceratitis capitata, Moscamed, pest free area, entry (of a pest), outbreak, pest absence, eradication

Resumen

La mosca del Mediterráneo (Ceratitis capitata, Wiedemann; Diptera: Tephritidae) es considerada como una de las plagas más destructivas en el mundo. Fue detectada por primera vez en México (en la frontera sur con Guatemala) en 1977, una vez que se había dispersado por toda la región Centroamericana. En 1982, utilizando un enfoque de MIP en áreas amplias incluyendo la técnica del insecto estéril, el Programa Moscamed, establecido por los gobiernos de México, Guatemala y Estados Unidos de América, fue exitoso en erradicar a la plaga de las áreas que había invadido en México. Entradas de plaga recurrentes en la forma de detecciones y brotes transitorios ocurren en los estados del sur de México fronterizos con Guatemala. El estatus libre de plaga se mantiene a través de acciones de erradicación cuya efectividad es verificada por medio de una extensiva e intensiva red de vigilancia que incluye 24,760 trampas. Utilizando la terminología de la Convención Internacional de Protección Fitosanitaria (CIFP), el estatus de plaga de la Mosca del Mediterráneo se puede definir para la mayor parte de México como “Plaga Ausente” (i.e. los sistemas de vigilancia confirman la ausencia de plaga en 28 de 32 estados) y como “Plaga Transitoria” (i.e. entradas de plaga que no resultan en establecimiento después de la aplicación de medidas fitosanitarias para su erradicación) para los estados fronterizos en el sur incluyendo Chiapas, Tabasco y Campeche y para Baja California estado fronterizo en el

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The Mediterranean fruit fly (Ceratitis capitata (Wiedemann); Diptera: Tephritidae) (hereafter medfly) is among the most destructive insect pests worldwide due to the direct damage it causes to a wide range of high value fruit and vegetable crops, resulting in significant yield reductions and loss of quality. In addition, quarantine restrictions imposed by medfly-free countries impact horticultural exports from countries where the pest is present (Gutiérrez Samperio 1976; Liquido et al. 2013).

The first record of medfly presence in the Americas is believed to be in Brazil between 1901 and 1905 (Enkerlin et al. 1989). In Central America, the introduction of medfly was first reported in Costa Rica in 1955. From there it spread throughout the Central American region in spite of several efforts to contain it, finally reaching Guatemala in 1976 and Chiapas, the Mexican State bordering Guatemala, in 1977 (Steiner 1967; Rhode et al. 1973; Gutiérrez Samperio 1976; Rohwer 1992). By 1979 the pest had invaded the Pacific coast of Chiapas spreading rapidly mainly along the coffee (Coffee arabica L.; Gentianales: Rubiaceae) belt as far as 300 km from the Guatemalan border. The barrier has been maintained based on extensive surveillance of the El Pino mass-rearing facility in Guatemala, with a production capacity of over 2,000 million sterile medfly males per week, increased considerably the availability of sterile insects to help maintain the containment barrier (Rendon et al. 2000; Gutiérrez Ruelas et al. 2013). The construction in 1996 of the El Pino mass-rearing facility in Guatemala, with a production capacity of over 2,000 million sterile medfly males per week, increased considerably the availability of sterile insects to help maintain the containment barrier (Rendon et al. 2000). The first record of medfly presence in the Americas is believed to be in Brazil between 1901 and 1905 (Enkerlin et al. 1989). In Central America, the introduction of medfly was first reported in Costa Rica in 1955. 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The width of the medfly containment barrier, which abuts and protects the PFA, has been relatively stable, although this has also been a function of the financial resources available each year. The containment barrier is physically located next to the PFA, which is not part of the containment barrier. The PFA in Mexico includes the whole country, although special attention is focused on Chiapas and southern Tabasco as these States are exposed to recurrent medfly transient entries that are immediately eliminated according to the corrective action plan. However, the PFA also includes Belize and areas in northern and western Guatemala, where its size varies according to the location of the containment barrier.

The spatial location of the containment barrier is dynamic in relation to the PFA of the Mexican States bordering Guatemala; its geographical position in Guatemala fluctuates with the leading edge of the infestation moving towards or away from the PFA depending on the progress being made in containing and eradicating the pest (Programa Moscamed 2013b). In years that are favorable for the Moscamed Program, the PFA in Guatemala grows as the barrier moves an average of 20-30 km away from the Mexican border. In unfavorable years with large pest pressure the barrier has had to move back towards the Mexican border and in extreme cases partially into the PFA of Chiapas and Tabasco, sometimes requiring major efforts and emergency funding to be able to regain the PFA status and to move the barrier back into Guatemala.

The containment barrier consists of 3 areas, which follow the pest infestation gradient from no pest presence in the PFA in the west and north to the increasingly infested areas in the east and south where the pest pressure is the greatest (Fig. 1 and Fig. 2). The 3 areas of the containment barrier are as follows:

1. The Eradication or Low Prevalence area (LPA) is located within Guatemalan territory between the PFA and the outer limit of the suppression area. Since populations occur very sporadically, this area is also known as low prevalence area (LPA), and when medflies are detected, their populations are subjected to intensive area-wide eradication activities.

2. The Suppression area is located between the eradication or LPA and the monitoring area; it is here that populations start to occur regularly, and thus where the leading edge of the infestation fluctuates annually. In this area population reduction tools are used for pest suppression in preparation for population eradication.

3. The Monitoring area is located next to the suppression area where populations are well established and are only monitored in advance of the moving containment barrier, representing the next area of program intervention (Programa Moscamed 2013a; Hendrichs et al. 2005).

**Terms and Definitions**

For most of this article, terms are used as defined in the Glossary of Phytosanitary Terms (International Standard of Phytosanitary Measure [ISPM No. 5]) of the International Plant Protection Convention (IPPC) (https://www.ippc.int/en/core-activities/standards-setting/ispm/#publications), as well as terms and definitions contained in ISPM No. 8 “Determination of the Pest Status in an Area” and No. 26...
Establishment of pest free areas for fruit flies (Tephritidae) (FAO 1998, 2006, 2013, 2014). Some of the terms have no formal definition, therefore definitions are proposed within the context of the article. The relevant terms and definitions are the following:

**Absence.** If there are no records of the presence of the pest in the general surveillance data of an area, it may be reasonable to conclude that a pest is or has always been absent (FAO 1998).

**Detection.** A recent individual entry of a pest, that may survive in the immediate future, but is not expected to become established (no official definition is available). Operationally, the Moscamed Program defines an entry as a detection (rather than as an outbreak) when only one male fly or one unmated female is found and the subsequent delimitation trapping does not detect any additional individuals (Programa Regional Moscamed 2010).

**Entry (of a pest).** Movement of a pest into an area where it is not yet present, or present, but not widely distributed and being officially controlled (FAO 2013). For the purpose of this review, a medfly entry can be classified as a detection or outbreak depending on the characteristics of the event (see definition of terms). A detection or outbreak is considered to be a pest transient entry into an area where it is not yet regarded as present.

**Eradication.** Application of phytosanitary measures to eliminate a pest from an area (FAO 2013). This term has been controversial among applied entomologists, who have defined the term eradication in many ways. Newsom (1978) defined eradication of a pest population as “the destruction of every individual in an area surrounded by natural or man-made barriers sufficiently effective to prevent reinvasion except through the intervention of man”. Apart from medfly eradication described in this paper, other examples that are consistent with this definition include: medfly (C. capitata) and oriental fruit fly (Bactrocera dorsalis, (Hendel)) eradication from California and Florida on multiple occasions, medfly eradication from Chile and Argentina, Mexican fruit fly (Anastrepha ludens, (Loew)) eradication from the Mexican states of Baja California, Sonora, Coahuila and northern Sinaloa and melon fly (B. cucurbitae, (Coquillett)) eradication from Okinawa, Japan (Enkerlin 2005).

**Establishment.** Perpetuation, for the foreseeable future, of a pest within an area after entry (FAO 2013).

**Leading edge of infestation.** Within an infested area that is subjected to population suppression actions and that is adjacent to an eradication or LPA where eradication actions are enforced, the leading edge of the infestation is here defined as a series of geographical points.
(or trap sites) nearest to the limits of the PFA where the pest’s density as inferred from annual trap catches match the density as inferred from mean weekly trap catch over a year for the entire suppression area.

**Outbreak.** A recently detected pest population, including an incursion, or a sudden significant increase of an established pest population in an area (FAO 2013). Operationally, the Moscamed Program categorizes a pest transient entry as an outbreak following the detection of more than one male fly, a mated female fly or any immature stages of the pest (Programa Regional Moscamed 2010).

**Pest Free Area (PFA).** An area where a specific pest does not occur as demonstrated by scientific evidence and in which, where appropriate, this condition is being officially maintained (FAO 2013).

**Presence.** A pest is present if records indicate that it is indigenous or introduced (FAO 1998).

**Suppression.** The application of phytosanitary measures in an infested area to reduce pest populations (FAO 2013). Hendrichs et. al. (2005) state that the main objective of suppression is to maintain the pest population below an agreed and acceptable economic injury level and/or prevalence level, in contrast to eradication which implies the elimination of a local population of a pest. A good example of fruit fly suppression is the South African Mediterranean Fruit Fly Suppression Program, which successfully suppressed medfly populations using an area-wide SIT based IPM approach, creating internationally recognized low pest prevalence areas (Barnes et al. 2004).

**Transience.** The pest has been detected as an individual occurrence or an isolated population that may survive into the immediate future, but it is either not expected to establish and appropriate phytosanitary measures, including surveillance, are being applied, or it may establish and appropriate phytosanitary measures have been applied for its eradication (FAO 1998).

### Surveillance Network (Trapping and Fruit Sampling)

Since medfly eradication from Mexico in 1982 (Hendrichs et al. 1983), the National Plant Protection Organization of the Mexican Government, SENASICA-SAGARPA, has maintained an extensive country-wide surveillance network for early detection of transient entries (detections and outbreaks) of medfly and other non-native fruit fly pests using adult fly traps and attractants. This network is operated based on the International Standard on Phytosanitary Measures ISPM No. 6 Guidelines for Surveillance (FAO 2011) and the National Phytosanitary Legislation NOM-076-FITO-1999 (Diario Oficial 2000; http://www.senasica.gob.mx/?doc=700).

The network of traps located in the State of Chiapas is operated by the Moscamed Program. The network consists of traps placed at all higher risk sites, including natural pest pathways, such as coffee growing areas, which extend uninterrupted from infested areas in Guatemala into the State of Chiapas, other preferred hosts, official and unofficial border crossings, touristic sites, fruit markets, fruit dumps, airports, seaports and train and bus stations (SENASICA 2010). The trapping network in the rest of the country is operated by the Fruit Fly National Surveillance System under the management of State Plant Protection Committees, which are extensions of the National Plant Protection Organization of Mexico.

The types of traps deployed and serviced are the Jackson Trap baited with the male medfly specific attractant Trimedlure (TML) and the Fase-IV trap baited with a synthetic protein-based attractant (Bio lure®), which is biased toward females, but also captures males (IAEA 2003 (http://www-pub.iaea.org/MTCD/publications/PDF/te_1574_web.pdf); Heath et al. 2004). In areas where SI is carried out with sexing strains (nearly only sterile male releases) fly sorting from traps is more efficient in the Phase IV traps—which capture mainly wild females because extremely few mass-reared sterilized females are released—compared with trimedlure, which captures predominantly males—so that most of captured males are, sterile males of the released mass-reared strain. Average trap density is 2 traps/km², and trap checks are conducted at 14-day intervals. The layout of the trapping network follows an irregular pattern according to the predetermined pest risk sites. These procedures are consistent with national (NOM-076-FITO-1999; Diario Oficial 2000) and international phytosanitary standards (FAO 2006).

The Moscamed Program currently operates a trapping network in Chiapas of 14,710 traps with an average number of trap services of 382,460 per year (Programa Moscamed 2013a). In the rest of the country the trapping network consists of 10,050 traps. In recent years, the trapping network went through an in depth review and restructuring to assure trap placement in relevant pest risk sites, upgrading trap sensitivity by complementing the traps commonly used in trapping networks with highly sensitive traps, namely the Yellow Panel Trap and C&C Trap (DGSV-SENASICA 2007; Enkerlin et al. 2012; IAEA 2003, Programa Moscamed 2013a). In addition, the concept of permanent sentinel trapping (or intensive trapping) was introduced by the program in 2010 and at sites characterized as high-risk based on the historical profile of pest occurrence, trap density was increased by at least 5-fold (FAO 2006; Programa Regional Moscamed 2012a). With this restructuring, the overall sensitivity of the trapping network was significantly increased, allowing for a higher probability of capture and thus for earlier detection of medfly transient entries, verification of pest eradication and confirmation of pest absence (Lance & Gates 1994; Enkerlin 1997; Shelly et al. 2014). Traps are also used for the purpose of delimitation of entries as part of a corrective action plan. Any single adult fly caught either in the PFA or in the LPA triggers a delimiting response as presented below.

A stratified random fruit sampling is also used as a medfly surveillance tool mainly along the border region of the State of Chiapas with Guatemala. This surveillance tool is used both to complement the information provided by traps and as a stand-alone detection tool. Fruit samples of the primary medfly hosts, mainly coffee, guava (Psidium guajava L.; Myrtaceae: Myrtaceae), caimito (Chrysophyllum cainito L.; Rosales: Sapotaceae), mandarin (Citrus reticulata Blanco; Sapindales: Rutaceae) and sour orange (C. aurantium L.), are systematically collected in specific higher risk sites, and this effort is increased at certain times of the year according to host phenology and historical profile of medfly occurrence (Programa Regional Moscamed 2012b). Fruit sampling is also carried out during 3 life-cycles of the pest as part of the eradication protocol to delimit a medfly catch in a trap. Fruit samples are collected within one square kilometer surrounding a medfly entry to characterize the extent and severity of the infestation. After eradication actions have concluded, intensive fruit sampling activity is continued during one additional life-cycle of the pest, together with trapping to confirm pest eradication.

### Global Positioning and Geographic Information Systems

The 24,760 traps (14,710 in Chiapas and 10,050 in the rest of the Mexican States) that make-up the trapping network are georeferenced using the Global Positioning System (GPS). A database of medfly captures allows for precise spatial and temporal distribution analysis through the use of geographic information systems (GIS) (Midgarden & Lira 2008; IAEA 2006). Data of adult captures, transformed into aver-
Assessing Medfly Infestation Fronts

Medfly transient entries from infested areas in Guatemala into the PFA in Chiapas and Tabasco follow 3 distinctive and predictable pathways along 3 regions or fronts (Fig. 2): (1) the Southwest - Soconusco front (SW), (2) the Northwest - Comalapa front (NW), and (3) the North Transversal Strip–Marques de Comillas front (NTS).

The SW front is located on the Pacific coast along a continuous coffee belt (ca. 500-1500 m asl) that extends from east to west in Guatemala towards the Mexican border and into the State of Chiapas. The Soconusco region in Chiapas is a PFA, where also papaya (Carica papaya L.; Brassicales: Caricaceae), mango (Mangifera indica L.; Sapindales: Anacardiaceae) and rambutan (Nephelium lappaceum L.; Sapindales: Sapindaceae) are grown and exported to the USA and other countries.

The NW front includes the city of Huehuetenango, where primary hosts such as citrus, guava, figs and white sapote (Cosmocarca edulis La Llave & Lex; Sapindales: Rutaceae) are abundant in backyards and the surrounding rural areas, where both small scattered and large coffee plantations occur.

The NTS front faces the PFA in the north of Chiapas, south of Tabasco and north Guatemala and includes, in Guatemala, the coffee growing regions of Cobán and Barillas. In this case, the coffee production areas are not continuous and do not extend into Chiapas as in the SW front. This region mainly combines the production of industrial crops, including rubber (Hevea brasiliensis Willd.; Malpighiales: Euphorbiaceae) and African oil palm (Elaeis guineensis Jacq.; Arecaceae) with extensive cattle ranches. No fruit or vegetable crops are grown for export in this region.

The Leading Edge of the Infestation

The annual leading edge for each of the 3 infestation fronts located within Guatemala was identified and defined using GIS and the database containing historical information on medfly population abundance. For each front, the total number of fertile adult flies per year (2004 to 2013) captured in traps in the suppression area (fly catches within the eradication area or LPA are not included in the assessment of the leading edge) were summarized in a grid of 25 km² (5 x 5 km) cells. In each of the cells, the weekly mean total capture ± 2 SD was calculated for each year. The geographical location of the leading edge of the infestation for each front was determined for each year by selecting the 25 km² cell nearest to the limits of the PFA where medfly populations matched or exceeded the mean weekly counts over a year for the entire suppression area (Fig. 3). The distance of the leading edge of each of the 3 fronts to the limits of the PFA in Chiapas was computed for each individual year as described in the Data Analysis section. In the case of Tabasco and Campeche the distance of the leading edge to the limits of the PFA was not computed as the medfly transient entries during this time period were very rare.

Description of the Eradication Protocol

A medfly transient entry into a PFA (any single adult male fly or unmated female finding) will automatically trigger an increase of trap density from 2 to 10 traps/km² within a square area of 9 km² surrounding the trap with the capture. If no more flies are captured after one biological cycle the delimitation trapping is ended, the transient entry is defined as detection, and the normal trap density (i.e., 2 traps/km²) is reestablished.

Once a medfly transient entry in a PFA is defined as an outbreak (following the detection of more than one male fly, a mated female fly or any immature stages of the pest) specific detection, suppression and eradication actions are immediately enforced (FAO 2006). Actions are designed to eliminate outbreaks and maintain the PFA status. The type and intensity of the actions are defined in specific eradication protocols (FAO 2006, 2014; Programa Moscamed 2010); they depend on the extent and severity of the outbreak and may include several of the following activities: delimitation survey using specific traps, ground and/or aerial bait sprays, bait stations, fruit stripping, ground and/or aerial release of sterile flies, verification survey and, if necessary, enforcement of additional quarantine measures.

If a transient entry is defined as an outbreak, delimitation trapping is kept at 10 traps/km² in the 9 km² core area. In addition, the delimitation trapping is extended from 9 km² to 25 km², and trap density is increased from 2 to 4 traps/km² in the additional area surrounding the 9 km² core area. Delimitation trapping continues for 2 additional biological cycles. An outbreak is considered to be eradicated after completion of a period of 3 biological cycles after the last detection with no further fly findings (FAO 2013, 2006; Diario Oficial 2000; Programa Moscamed 2010). Once eradication actions have been finalized, the Moscamed Program applies verification trapping for an additional life-cycle to confirm eradication using 5 traps/km² within the 9 km² core area (Programa Moscamed 2010).

Assessment of the Life Cycle

In order to estimate the lengths of life-cycles and the number of potential generations of the medfly, the Tassan degree-day model (Tassin et al. 1982) was applied in the PFA of Marques de Comillas, Chiapas, for the years 2011, 2012 and 2013. This area facing the NTS front, was selected for this analysis since it is the area with the most medfly transient entries since 2011 (92.1%). The other 2 relevant PFAs are Soconusco facing the SW front with an average of only 3 (6.6%) medfly transient entries, and Comalapa facing the NW front with an average of less than 1 entry (1.3%) from 2011 to 2013. To run the model, maximum and minimum daily temperatures provided by the meteorological stations of the Comisión Federal de Electricidad of Mexico were obtained (CFE, 2011, 2012, 2013). The development thresholds used were 9.7 °C and 325.2 Degree Days (°D)—142.8 °D for eggs and larvae and 182.4°D for pupae—for the egg to adult and 16.6°C and 44.2°D for the adult preoviposition period.

Probabilistic Model for Fruit Fly Detection Using Traps

The probabilistic model of Enkerlin (1997), computes the probability of catching at least 1 adult medfly from a given population size at a given distance from a trap using a Jackson trap baited with Trimeurel and deployed at various densities. For this purpose, the model uses the exponential regression equation (p = ab²) obtained from a release-recapture field experiment, where, (p) is the probability of catching a given fly, (a) the intercept to the “y” axis, (b) the slope of the curve or probability of capture and (d) is the initial distance of a fly from a trap. This probability value (p) is entered into a probabilistic formula [P(0) = (1-p)] to calculate the probability of capturing zero flies from a given population (n). The binomial expansion equation (P(0) + q = 1) is then applied to compute the probability (q) of catching at least 1 fly for the presence of different
numbers of medflies and different trap densities (Lance & Gates 1994; Barclay et al. 2005). Through this model the probability of catch for a trap density of 10 traps/km² was assessed, as this is the density applied by the Moscamed Program for the delimitation survey after a fly entry and for sentinel trapping at high risk sites to increase the probability of catch (Programa Regional Moscamed 2012). From an initial population of 3 gravid females, an average 3-fold increase per generation is assumed based on data on medfly population growth rate observed under the fluctuating environmental conditions of Guatemala and Chiapas, Mexico and based on field tests conducted in large cages placed on coffee plantations in Guatemala (Rendón et al. 2004; FAO 2007).

**Data Analysis**

The trapping data produced by the Moscamed Program from 1982 to 2013 (31 years) were used to assess the general trend of medfly entries into the PFA of Chiapas and Tabasco. These data were transformed to average FTD and used as input information in a GIS (IAEA 2003, 2006) to assess the medfly spatial and temporal abundance and distribution in the PFA of Chiapas and Tabasco, which are the States subjected to medfly population pressure from the leading edge of the infestation in Guatemala (Programa Moscamed 2013b).

Moreover, trapping data generated from 2004 to 2013 were used to establish the relationship between the distance of the leading edge of medfly infestations in Guatemala to the PFA (independent variable “x”) and the number of medfly transient entries into the PFA of Chiapas (dependent variable “y”). The degree of association between the 2 variables was measured using the non-parametric Spearman Correlation analysis using ranks. A perfect Spearman correlation of +1 or -1 occurs when the rank of each of the variables is a perfect monotone function of the other (Myers & Well 2003). This time period was selected for the correlation analysis, since the program`s database contains information in an organized and systematic manner for this type of analysis only from 2004.

**Historical Data**

Since the medfly was eradicated from Chiapas in 1982, the Moscamed Program has effectively protected the southern border States of Mexico with Guatemala (i.e., Chiapas, Tabasco and Campeche) and all the rest of Mexico and the USA from establishment of medfly populations originating in the infested areas in Guatemala and rest of Central America.

Historical trapping data of the Moscamed Program for the period from 1982 to 2013 showed recurring medfly transient entries from Guatemala into the PFA in Chiapas every year and more sporadic transient entries into Tabasco. During this period, 96.4% of all medfly transient entries were found in Chiapas and only 3.5% in Tabasco (mostly
in the Tenosique area, a small town located on the southern border of this State with Guatemala) (Figs. 4 and 5).

During these 31 years, the highest FTD (flies trapped per day) population index ever recorded was 0.00023 in the State of Chiapas in 2007, the year with the highest historical number of medfly transient entries into Mexico (Fig. 6). This population level was 43 times lower than the level established for an area of low pest prevalence (FTD = 0.01), consistent with a PFA where a pest was not present but was subject to transient entries and the systematic application of phytosanitary measures to maintain this condition (IAEA 2003; FAO 2006).

The only other Mexican States where medfly has ever been detected are Campeche (2 transient entries, one in 1998 and one in 2005) and Baja California (1 transient entry in 2004). The latter entry was characterized as an extensive outbreak and occurred in Tijuana City along the Northwest Mexico-USA border between this State and California. The outbreak was declared eliminated in 2005 after a 9-month area-wide eradication effort by the Mexican National Plant Protection Organization (SENASICA-SAGARPA) in collaboration with the United States Department of Agriculture (USDA), the California Department of Food and Agriculture (CDFA) and the Government of the State of Baja California (Programa Moscamed 2013b; Gutierrez-Ruelas et al. 2013). No Medflies have ever been detected in the other 28 Mexican States (Fig. 5).

Medfly transient entries into the PFA in Chiapas and Tabasco occurred when the pest overcame the containment barrier. Effectiveness
of suppression and eradication actions within the containment barrier and the influence of climate and other ecological factors on the reproductive rate of the pest affected the distance of the leading edge of the medfly infestation in Guatemala to the limits of the PFA in Chiapas and Tabasco. This in turn determined the geographical location of the containment barrier. Lower average temperatures in the region were shown to reduce the reproductive rate of the pest. This occurred in years with higher rainfall and coincident reduced sunlight (“La Niña phenomenon”), which tended to lower temperatures. In these La Niña years or in years considered to be average in terms of temperature and rainfall, the program was able to effectively maintain or even advance the location of the barrier to the east and south.

In contrast, years with temperatures above average, often characterized by rainfall below average (i.e., characterized as “El Niño” years), favored higher reproductive rates of the pest (Herrera 1998). The fluctuations in medfly trap captures in infested areas in Guatemala and their relationship to El Niño events and hurricanes are shown in Fig. 7. This temperature effect may be exacerbated in years of high availability of coffee berries, since they are the primary medfly host in Guatemala. High availability of coffee berries could be attributed to favorable growing conditions and low coffee prices in the international market, which may result in reduced coffee harvest and high volumes of coffee berries left in the field. Years that favored high build-up of medfly populations led to higher population pressures against the containment barrier and the westward movement of the leading edge of the infestation (Fig. 3). As a consequence, in such years the containment barrier was moved closer to the limits of the PFA in Chiapas and Tabasco.

Medfly population pressure was manifested through natural dispersal and movement by humans transporting the pest within fruit. Apparently pest dispersal behavior was triggered by intraspecific competition that resulted from higher population densities combined with changes in environmental conditions, such as lack of host fruits (e.g., after a full coffee harvest) or the abrupt onset of hot and dry weather (e.g., el Niño climate type) (Bateman 1972). Dispersal of the pest may have been aided by dominant wind currents or high speed winds common during tropical storms, which could transport adults to nearby as well as more distant areas (Enkerlin 1987; Midgarden & Lira 2008; Puche et al. 2005). For example, marked sterile male Medflies ground released in Guatemala were caught more than 50 kilometers downwind from the release site (Villatoro et al. 2014).

Alternatively, pest movement from Guatemala to the PFA in Mexico could have occurred when agricultural workers carried small amounts of infested fruit during travel. Workers moved locally back and forth across the border from Guatemala to the Mexican States of Chiapas and Tabasco during the coffee, mango, banana and sugarcane harvest seasons. Host fruit also may have been carried by the public or mi-
Relationship Between the Distance from the Leading Edge of the Infestation to the Limits of the PFA and the Number of Medfly Transient Entries into the PFA

The analysis of the trapping data from 2004 to 2013 for the SW and NTS fronts showed a significant inverse Spearman correlation between distance and medfly transient entries: for the SW front \( P = 0.0001, \) \( df = 8 \) and for the NTS front \( P = 0.014, \) \( df = 8 \). This implied that the number of transient entries into the PFA decreased as the distance of the leading edge to the limits of the PFA increased (Fig. 3). However, for the NW front, statistical significance fell short by a small margin meaning that there were likely other factors influencing the relationship between the variables \( (P = 0.086, \ df = 8) \) (Table 2). Nevertheless, the correlation was negative confirming an inverse relationship between variables for this front as well. This correlation can be graphically observed in Fig. 3, where the annual locations of the leading edge of the infestation for the 3 fronts during the years 2004 to 2013 are shown.

On the SW front, 93% of the medfly transient entries into the PFA of Soconusco in Chiapas could be explained by natural movement of the pest from the leading edge of the infestation to the PFA. As the leading edge of the infestation moved away from the limits of the PFA the number of medfly transient entries (detections and outbreaks) in this area was reduced exponentially (Fig. 8, Table 3). Based on this correlation, when the leading edge of the infestation was 78 km or more from the limits of the PFA, the expected number of medfly transient entries into the Soconusco PFA decreased to an average of only 3.3 per year (Table 3). If the distance decreased to between 78 and 43 km, the expected number of transient entries increased to around an average of 14 per year; if it decreased between 43 and 22 km the expected number further increased to around 39, whereas, if the leading edge was less than 22 km from the PFA the expected average number of transient entries per year increased to over 200. In 2007 the leading edge was only 1.8 km from the PFA, and 329 medfly transient entries were recorded and the barrier had to be moved partially into Chiapas.

On the other hand, from 2011 to 2013, only 4, 0 and 6 medfly transient entries were recorded within the PFA of Soconusco, the lowest since medfly eradication from Chiapas in 1982. During this period, the SW front was between 78 and 93 km away from the limits of the PFA (Table 3).

The NW front faces the Comalapa PFA in Chiapas. On this front, only 57% of the medfly transient entries could be explained by natural movement of the pest from the distance of the PFA to the leading edge of the infestation in Guatemala. As with the NTS front (discussed below), the other likely variable was the non-regulated movement of infested fruit—in this case primarily as food for self-consumption by the agricultural work force that moved across the border from Guatemala to Chiapas in massive numbers during the months of Aug to Feb. Most of these temporal migrants harvested coffee in the extensive plantations located near the border region of Chiapas and Guatemala. No medfly transient entries occurred in the Comalapa PFA in 2011 and 2012, while only 2 medfly transient entries occurred in 2013 in this region. In these years, the NW front was 59.2, 61.6 and 64.5 km away from the limits of the PFA, respectively (Table 3).

For the NTS front, 74% of medfly transient entries could be explained by the distance of the leading edge to the PFA of Marques de Comillas. The remaining 26% could not be explained in this manner and may be influenced by other variables. As has been shown, historical data of infested fruit confiscated in quarantine checkpoints strategically placed in Guatemala to protect the PFA in northern Guatemala and Chiapas was documented through records of larvae intercepted in infested host fruit at 7 quarantine checkpoints strategically placed in Guatemala to protect the PFA. From 2004 to 2013, 383.1 metric tons of host fruits were confiscated yielding a total of 11,640 medfly larvae (0.03 larvae/kg) (Table 1).
transient entries increased to an average of 70 per year, whereas, with
the leading edge at less than 23 km the expected number of transient
entries per year increased to an average of 247 per year (in 2007 the
leading edge was 2.9 km from the PFA and 420 medfly transient entries
were recorded) (Table 3).

Pest Absence in the PFA of the Marques de Comillas Region
From Nov To May Period

During 2004–2013 most of the transient entries into the PFA of
Chiapas occurred in the Marques de Comillas region. In the last three
years (2011-2013), 92% of the entries occurred in this region, there-
fore, this site and time period were selected for the analysis to assess
pest absence. This PFA was exposed to the NTS front.

The initial medfly transient entries were detected in early Jun, with
the peak occurring in Aug or Sep and the last few entries detected in
Oct. This appeared to be the normal pest entry pattern in the Marques
de Comillas region (Fig. 9). With the exception of 1 transient entry in
2012 and 2 transient entries in 2013, no medflies were detected in this
area from Nov to May. Pest absence during the 7 months was verified
through intensive sentinel trapping at high risk areas and by upgrad-
ing trap sensitivity through the use of Yellow Panel and C&C traps and
stratified random fruit sampling of medfly primary hosts throughout
the year. Hosts abundant in this area during these 7 months included
coffee and other preferred hosts, such as caimito, guava, mandarin,
sweet orange (C. sinensis Osbeck), sour orange and mango. During the
years 2012 and 2013, the total number of samples collected and ana-
alyzed in this region was 17,944. From this total, 6,807, 7,445, 1,364 and
1,208 corresponded to coffee, guava, sweet orange and sour orange
fruits, respectively, without the detection of a single medfly larva (Pro-
grama Moscamed 2013b) (Fig. 10).

Pest absence in the PFA of the Marques de Comillas region during
these 7 months can also be inferred by evaluating climatic conditions
(i.e., temperature and rainfall), which were suitable for pest reproduc-
tion and population increase. The average temperature fluctuated
between 19.4 and 27.3 °C during these months, appropriate for pest
survival and rapid development. Heavy rains associated with frequent
tropical storms were common in Guatemala and Chiapas during the
summer months, and heavy rainfall could have been a factor that nega-
tively affected medfly populations through saturation of soils causing
pupal mortality or the reduction of natural protein sources available
to adults, thus depressing rates of reproduction (Enkerlin et al. 2014).
Nevertheless, in the Marques de Comillas region there was low rainfall
from Nov to May (average monthly rainfall was 107 mm from 2011
to 2013), and thus, the absence of medfly could not be attributed to
this climatic factor (Fig. 11). Based on temperature records and the
application of Tassan’s degree-day model (Tassan et al 1982) to these 7
months, up to 7 generations could have been produced between Nov
and May under the climatic conditions prevailing in the Marques de Comillas region (Fig. 12). Thus the combined effect of the abundance of primary hosts and suitable climatic conditions for population growth could have resulted in a rapid medfly population increase. Assuming the remaining presence of 3 gravid medfly females during the month of Nov in the PFA of the Marques de Comillas region in the northeast of Chiapas, a total of 7 generations in the time period between Nov and May and an average 3 fold generational increase, the total population could have increased to 81, 243, 729, 2,187 and 6,561 individuals in the F₁, F₂, F₃, F₄ and F₅ respectively (Rendón et al. 2004).

The probabilistic model to detect at least one adult medfly from a given population size using a density of 10 Jackson traps baited with TML per km² (equivalent to 25 traps/mile², which is the minimum density used by the program for intensive trapping in high risk sites and for delimitation trapping after detecting a transient entry), indicated that the expected probability of catching at least one adult fly was approximately 94% for the F₁ and nearly 100% for F₂ to F₅ (Enkerlin 1997, Programa Moscamed 2013a). Lance & Gates (1994) determined through a similar mathematical probabilistic model that 10 Jackson traps baited with TML per km² (10 traps/mile²) would detect medfly presence with a high probability (99.9%) within a few generations after the pest entry. Shelly et al. (2014), found 99.9% probability of catching at least one male using 5 TML traps per 2.59 km² given population size using a density of 10 Jackson traps baited with TML per 2.59 km² (5 traps/mile²) in a population of ca. 2,300 males, which would be reached in a few generations.

This trap density was one fifth of the density normally used by the Moscamed Program at high risk sites (Programa Moscamed 2013a). If a viable population were present during the months of Nov to May in the Marques de Comillas PFA, the population would have increased to 81, 243, 729, 2,187 and 6,561 individuals in the F₁, F₂, F₃, F₄ and F₅ respectively (Rendón et al. 2004).

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This trap density was one fifth of the density normally used by the Moscamed Program at high risk sites (Programa Moscamed 2013a). If a viable population were present during the months of Nov to May in the Marques de Comillas PFA, the population would have increased to detectable levels given the temperature, climatic and host conditions prevailing in the area. The absence of detections of medfly transient entries during this 7 month period since 2011, in spite of trapping at a high density by the Moscamed Program at high risk sites (Programa Moscamed 2013a). If a viable population were present during the months of Nov to May in the Marques de Comillas PFA, the population would have increased to detectable levels given the temperature, climatic and host conditions prevailing in the area. The absence of detections of medfly transient entries during this 7 month period since 2011, in spite of trapping at a high density by the Moscamed Program at high risk sites, indicated that outbreaks were either eliminated or that the few individuals left were unable to establish a population and became extinct. Extinction of small populations due to the Allee effect (i.e., positive density dependence) where an individual’s fitness decreases with declining density of its population is a well-known phenomenon in invasion ecology (Liebold & Tobin 2008).

### Analysis of Outbreaks

From 2010 to 2013, all medfly transient entries into the PFA in Chiapas—that were defined as outbreaks along the 3 fronts—were delimited within a 25 km² area using traps and collecting fruit samples according to the eradication protocol described above. An analysis of these outbreaks showed that in 93.2% of these transient entries populations did not expand beyond the central square kilometer (core area), 6.3% had moved into the next 8 peripheral square kilometers and only 0.5% had moved to the 16 square kilometer peripherals. In addition, on average, 99.3% of outbreaks were no longer detected be-
Enkerlin et al.: Mexico largely free of Ceratitis capitata

Beyond the first biological cycle ($F_1$) and only 0.75% of all cases managed to produce a $F_3$ generation within the core area (i.e., central square kilometer) (Table 4). Therefore, when analyzing each medfly transient entry individually, results showed that although medfly transient entries into Chiapas and Tabasco were recurrent, populations did not become established.

In summary, since 1982, all medfly transient entries (detections and outbreaks) that occurred in Mexico (Chiapas and Tabasco) and the few that occurred in Campeche (2) and Baja California (1), were effectively eliminated through the application of the eradication protocol (FAO 2006, 2014; Programa Regional Moscamed 2010). Using the IPPC terminology, the phytosanitary status of the pest for the border Mexican States of Chiapas, Tabasco, Campeche and Baja California, could be defined as “Pest Transient” (i.e., pest entry that does not result in establishment after applying appropriate phytosanitary measures for its eradication), and for the rest of Mexico as “Pest Absent” (i.e., no records of the presence of the pest confirmed by surveys) (FAO 1998).

### Economic Analysis and Benefits

A retrospective benefit-cost analysis was conducted for the Moscamed Program for the period 1978 to 2008 (IICA 2009). The study revealed that the investment made by the Mexican Government together with the Governments of the United States of America and Guatemala in protecting the PFA in the 3 countries resulted in a substantial

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**Table 3. Mediterranean fruit fly transient entries (detections and outbreaks) to the pest free areas (PFAs) of Soconusco, Marques de Comillas and Comalapa, Chiapas, Mexico, and distance from the leading edge of the infestation in Guatemala to the PFAs in Chiapas.**

| YEAR | SOCONUSCO | MARQUES DE COMILLAS | COMALAPA |
|------|-----------|---------------------|----------|
|      | No. entries (detections + outbreaks) | Distance to leading edge (km) | No. entries (detections + outbreaks) | Distance to leading edge (km) | No. entries (detections + outbreaks) | Distance to leading edge (km) |
| 2004 | 15 | 42.7 | 12 | 41.4 | 7 | 29.5 |
| 2005 | 50 | 22.9 | 78 | 23.2 | 9 | 14.5 |
| 2006 | 41 | 32.7 | 16 | 52.4 | 8 | 37.4 |
| 2007 | 329 | 1.8 | 420 | 2.9 | 24 | 34.9 |
| 2008 | 113 | 6.2 | 75 | 2.9 | 13 | 37.4 |
| 2009 | 25 | 22.1 | 42 | 27.9 | 5 | 57.3 |
| 2010 | 20 | 43.1 | 48 | 49.0 | 2 | 28.7 |
| 2011 | 4 | 92.7 | 26 | 49.9 | 0 | 59.2 |
| 2012 | 0 | 92.8 | 24 | 45.2 | 0 | 61.6 |
| 2013 | 6 | 78.2 | 89 | 34.2 | 2 | 64.5 |

*Distance between leading edge of the Mediterranean fruit fly infestation in Guatemala and the PFA in Chiapas.
Fig. 9. Numbers of Mediterranean fruit fly transient entries (detections and outbreaks) per month during the years 2011-2013 into the PFA of Marques de Comillas, Chiapas, for the North Transversal Strip–Marques de Comillas (NTS) front.

Fig. 10. Number of fruit samples collected during 2012 and 2013 in the Marques de Comillas PFA in Chiapas, Mexico, reflecting availability of Mediterranean fruit fly hosts and fruit phenology in this region.
positive economic return. The benefit-cost ratio for Mexico over this
time period was 112 to 1, clearly indicating that the Mexican Govern-
ment made the right decision in embarking on an area-wide integrated
pest management program aimed at preventing the establishment in
the country of this devastating pest.

Maintaining Mexico free of medflies allowed a substantial growth
of the horticultural industry, which generated foreign currency from ex-
ports, created jobs in the rural areas and improved the nutrition of the
human population by expanding fruit and vegetable supply and con-
sumption at affordable prices (IICA 2009). From 1978 to 2008, the area
planted in Mexico with crops considered to be medfly hosts increased
from 745,080 to 1,081,975 ha and the production volumes increased
from 7.8 to 19.1 million tons, which were equivalent in 2008 to $4.3
billion USD in exports only. During this same time period, the number
of full time jobs that were created in the horticultural industry through-
out the country was an estimated 1.63 million (IICA 2009). There were
other benefits such as avoiding the cost of significantly increased in-
secticide use over more than 30 years in Mexico’s horticultural produc-
tion had the medfly’s northward advance not been stopped. Prevent-
ing increased insecticide use saved environmental costs and reduced
residues in fruits and vegetables. For California alone, Siebert & Cooper
(1995) projected a cost of over 1.5 billion USD per year if medfly were
allowed to establish there as well as a dramatic increase in insecticide
use, amounting perhaps to more than 640 tons of active ingredient an-
nually. Additional side benefits of the Moscamed Program included the
strengthened Mexican plant protection capacity and biocontrol infra-
structure. The program has generated spin-offs such as the Moscafrut
Program, also integrating the release of sterile insects, which has suc-
ceded in freeing ca. half of Mexico from the native pest Anastrepha
fruit flies (Gutiérrez-Ruelas 2013).

Conclusions

The current pest status of the Mediterranean fruit fly in Mexico is
“Absent” with the pest having been eradicated in 1982, and surveil-
ance based on regular servicing 24,760 medfly traps (14,710 in Chi-
apas and 10,050 in the rest of Mexico) country-wide confirming con-
tinued pest absence.

Recurrent medfly entries into Mexico along the border States of
Chiapas and Tabasco with Guatemala were explained in 57 to 93%
instances by the distance from the leading edge of the infestation in

Table 4. Locations of Mediterranean fruit fly entries that were defined as outbreaks in the pest free areas (PFA) of Chiapas, Mexico, for the years 2010-2013 in relation to delimitation trapping after first entry, and their transience during the first, second or third estimated life cycles after the initial detection.

| Year | Entries | Biological cycle (%) |
|------|---------|----------------------|
|      | Total   | 1 km² core area | 8 km² peripherals | 16 km² peripherals | First (P) | Second (F₁) | Third (F₂) |
| 2010 | 70      | 59              | 10               | 1                | 100      | 0           | 0         |
| 2011 | 39      | 27              | 3                | 0                | 97       | 0           | 3         |
| 2012 | 23      | 23              | 1                | 0                | 100      | 0           | 0         |
| 2013 | 97      | 97              | 0                | 0                | 100      | 0           | 0         |
| Total| 221     | 206             | 14               | 1                | —        | —           | —         |
| %    | 100     | 93.2            | 6.3              | 0.5              | —        | —           | —         |
| Mean | —       | —               | —                | —                | 99.25    | —           | 0.75      |
Guatemala. Entries into the border states are “Transient” as they have been systematically eliminated through the effective application of the eradication protocol for medfly outbreaks. This has allowed Mexico to maintain its medfly-free status and continue exports to other medfly-free countries without quarantine restrictions.

The risk of medfly transient entries into the PFA in the southern border States of Chiapas and Tabasco and into Mexico as a whole decreases as the leading edge of the infestation is being pushed further away from the border with Guatemala by an active operational program among Guatemala, Mexico, and the USA, which integrates the area-wide release of sterile males with other suppression and containment methods.

Pushing the infestation front to the southern part of Guatemala would create a larger buffer zone between the fly-free areas in Southern Mexico and the leading edge of the infestation in Guatemala, greatly reducing the program cost and the risk of the pest spreading into Mexico and the USA and making viable the realization of full potential benefits for Guatemala. Therefore, it is essential that interested governments, horticultural industries and other relevant stakeholders assure the required level and opportune assignment of financial resources for the Moscamed Program to fulfill its next major objective, which is to eradicate the medfly from Guatemala.

The annual investment of the Government of Mexico in this area-wide program has paid-off amply in that the medfly-free status has allowed large expansion of fruit and vegetable production and exports from Mexico, generating economic growth, creating tens of thousands of jobs in rural areas and contributing to public health by increasing fruit and vegetable supply.

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