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 approach 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 (CIPF), 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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norte. La inversión tan significativa que el gobierno de México ha realizado en el Programa Moscamed por más de 30 años ha sido altamente rentable (tasa beneficio-costo de 112 a 1), cuando se compara con la industria hortofrutícola multimillonaria que se ha desarrollado durante este tiempo. Adicionalmente, a través de los años el programa involucró a sus propios investigadores así como a investigadores en otros países y organizaciones en innovación y optimización de importantes tecnologías. Se incluye técnicas de producción para una cepa genética de solo machos, torres de emergencia para moscas adultas, máquinas de liberación aérea, insecticida cebo de origen orgánico, estaciones cebo de larga duración, trampas Fase IV y atrayentes sesgados hacia captura de hembras, uso de sistemas de posicionamiento global para análisis de datos y predicciones y para la liberación rutinaria de moscas estériles. Estas herramientas han permitido un incremento en la efectividad del programa y han sido adoptadas en muchos países.

Palabras Clave: *Ceratitis capitata*, Moscamed, área libre de plaga, entrada (de plaga), brote, ausencia de plaga, erradicación

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; Gutierrez Samperio 1976; Rohwer 1992). By 1979 the pest had invaded the Pacific coast of Chiapas spreading rapidly mainly along the coffee (*Coffea arabica* L.; Gentianales: Rubiaceae) belt as far as 300 km from the Guatemalan border within the State of Oaxaca, which is directly northwest of Chiapas (Gutiérrez Samperio 1979; Schwarz et al. 1989).

Given the importance of the horticultural industries of Guatemala, Mexico and the USA and the potential for economic damage as a result of medfly establishment, the governments of the 3 countries decided to join efforts against this pest. The Mediterranean Fruit Fly Eradication Program (Moscamed Program) was created through a cooperative agreement signed between Mexico and Guatemala in 1975, a Memorandum of Understanding signed by Mexico and the USA in 1976, and a Cooperative Agreement signed by Guatemala and USA in 1981. Recently, the agricultural authorities of the 3 countries joined together in a trinational cooperative agreement that updated the previous bilateral agreements providing the Moscamed Program a more solid framework looking into the future.

The current goals of the Moscamed Program are: (1) to eradicate medfly entries into the pest free areas (PFA) in northern Guatemala, and the Mexican States bordering Guatemala, (2) to protect the medfly-free status in the rest of Mexico, USA, and Belize, and (3) in the medium to long-term eradicate the medfly from Guatemala.

The Moscamed Program initiated pest eradication efforts in Mexico in 1977 using an area-wide IPM approach (Klassen 2005). This included the sterile insect technique (SIT) (Knipling 1979; Patton 1980; Schwarz et al. 1989) for which a mass-rearing facility to produce 500 million sterile flies per week was built 1978-1979 in Metapa, Chiapas at the border with Guatemala (Schwarz et al. 1985). After 5 years (1978–1982) of intensive area-wide eradication efforts combining surveillance tools (i.e., trapping and fruit sampling), aerial and ground bait sprays, fruit stripping, the SIT, and regulatory measures, the medfly was considered eradicated from Chiapas, Mexico (LaBrecque 1982; Hendrichs et al. 1983; Szyniszewska & Tatem 2014).

Through the years, the program has done excellent R&D work in optimization and innovation of technologies. This includes: production techniques such as an only male genetic sexing strain (Robinson et al. 1999; Caceres et al. 2004), emergence towers and release machines (Dowell et al. 2005; Tween 2007; Leal-Mubarqui et al. 2013), organic targeted insecticide baits (Success 0.02 or GF120) (Moreno & Mangan 2002), long lasting bait stations (Piñero et al. 2014), Phase IV traps and female biased attractants (Heath et al. 2004; IAEA 2003), and use of global positioning systems for data analysis and forecasting and for routing aerial releases (Lira et al. 2008; Rendon 2008). These tools have led to increased program effectiveness. In the past 5 years, the program has gained over 20,000 km^2 (2 million ha) of territory pushing the infestation fronts away from the Chiapas-Guatemala border.

This paper presents the objectives and a number of sections describing basic concepts dealing with the components of insect containment barriers and phytosanitary terms and definitions. It also describes a series of tools used to assess pest status including surveillance, contingency plans for eradication, global positioning systems, the Tassan model for assessment of life cycles, a probabilistic model based on trap catch and a data analysis section. It goes on to sections presenting results including historical profile of pest entries, the relationship between the leading edge of the pest infestation and transient entries into pest free areas, an analysis of pest absence and outbreaks and a brief economic analysis of the Moscamed Program. The paper presents conclusions on the pest status of the Mediterranean fruit fly in Mexico and benefits accrued from the program.

The objectives of this review, covering a period of over 30 years since 1982 and more specifically the 10-year period since 2004, are to: (1) analyze how the spatial locations of the leading edge of medfly infestations in Guatemala affect pest transient entries into the PFA in Chiapas, Tabasco and Campeche (Mexican States bordering Guatemala subject to medfly entries), (2) discuss how other factors, such as favorable climatic conditions and movement of medfly-infested fruit, affect medfly transient entries into the PFA, and (3) characterize the pest status of medfly in these States and in Mexico as a whole.

Containment Barrier

Since 1982, the program shifted from a strategy of area-wide eradication to one of an area-wide containment barrier within Guatemalan territory. The barrier has been maintained based on extensive surveillance using specific traps and fruit sampling, quarantine checkpoints placed within Guatemala and at points of entry along the Mexico-Guatemala border, sterile fly releases and the systematic enforcement of a corrective action plan to respond to medfly transient entries from infested areas in Guatemala (Ortíz et al. 1986; Orozco et al. 1994; Villaseñor 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 with a minimum of insecticide use (Tween 2002).

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:

(2a) *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.

(2b) *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.

(2c) *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/ispms/#publications), as well as terms and definitions contained in ISPM No. 8 "Determination of the Pest Status in an Area" and No. 26

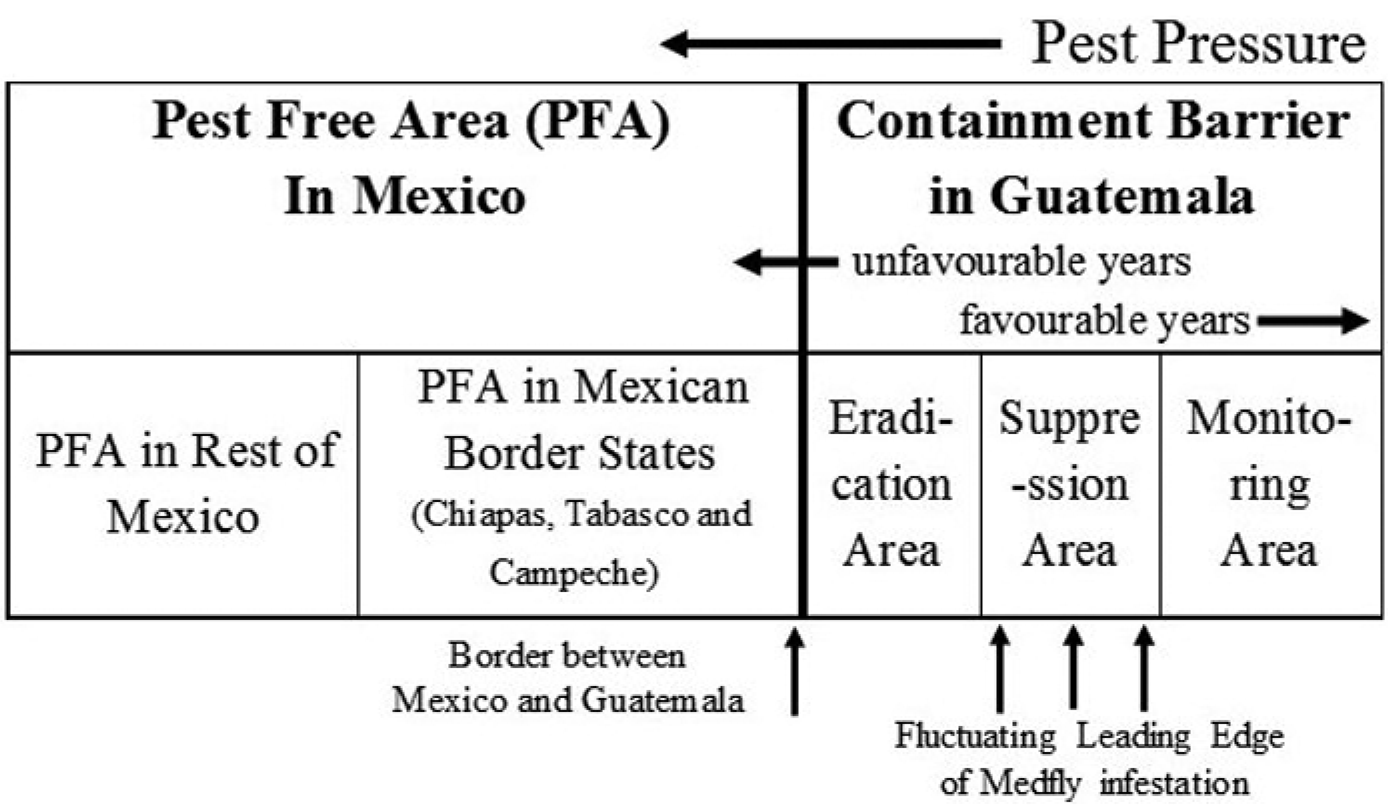


Fig. 1. Schematic representation of the Pest Free Area (PFAs) in Mexico and in the Containment Barrier in Guatemala, with its 3 working areas: the Eradication or Low Pest Prevalence Area (LPA) (2a), the Suppression Area (2b) and the Monitoring Area (2c). The Mediterranean fruit fly pressure is from the east and the south toward the west and the north, with the leading edge of the pest population infestation located at some point within the suppression area along the 3 main infestation fronts as described in the text. The case is shown where the border between Mexico and Guatemala is the limit of the PFA; however, in years of high pest pressure the barrier was partially moved into the PFAs of Chiapas and Tabasco, while in favorable years the PFA in Guatemala grew an annual average of 20-30 km with the containment barrier being moved away from the Mexico-Guatemala border.

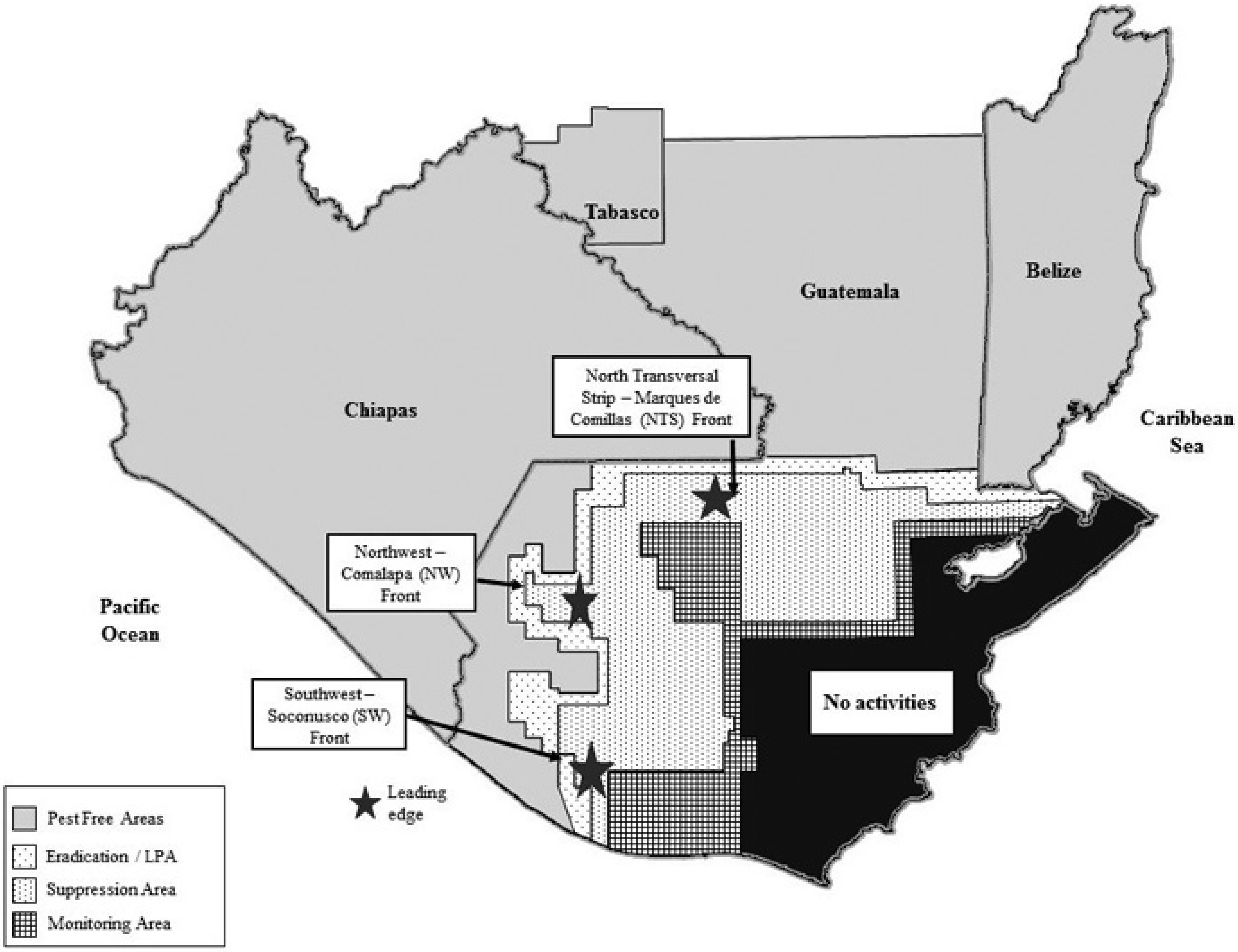


Fig. 2. Mediterranean fruit fly pest free areas (PFAs) in Chiapas, Tabasco, Guatemala and Belize, as well as the location of the current containment barrier, infestation fronts and leading edge of the infestation within Guatemala. The white areas to the southwest and southeast represent the Pacific Ocean and the Caribbean Sea, respectively.

"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 (Biolure®), 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 SIT 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/km^2, 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 guava* L.; Myrtales: 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 average number of flies per trap per day (FTD), allow assessment of relative population density in space and time (IAEA 2003).

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 (*Casimiroa 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 (H*evea 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 (from 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 km^2 (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 km^2 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/km^2 within a square area of 9 km^2 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/km^2) 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/km^2 in the 9 km^2 core area. In addition, the delimitation trapping is extended from 9 km^2 to 25 km^2, and trap density is increased from 2 to 4 traps/km^2 in the additional area surrounding the 9 km^2 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 lifecycle to confirm eradication using 5 traps/km^2 within the 9 km^2 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 (Tassan 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 Trimedlure and deployed at various densities. For this purpose, the model uses the exponential regression equation ($p = ab^d$) 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 [$P(0) = (1\text{-}p)^n$] 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

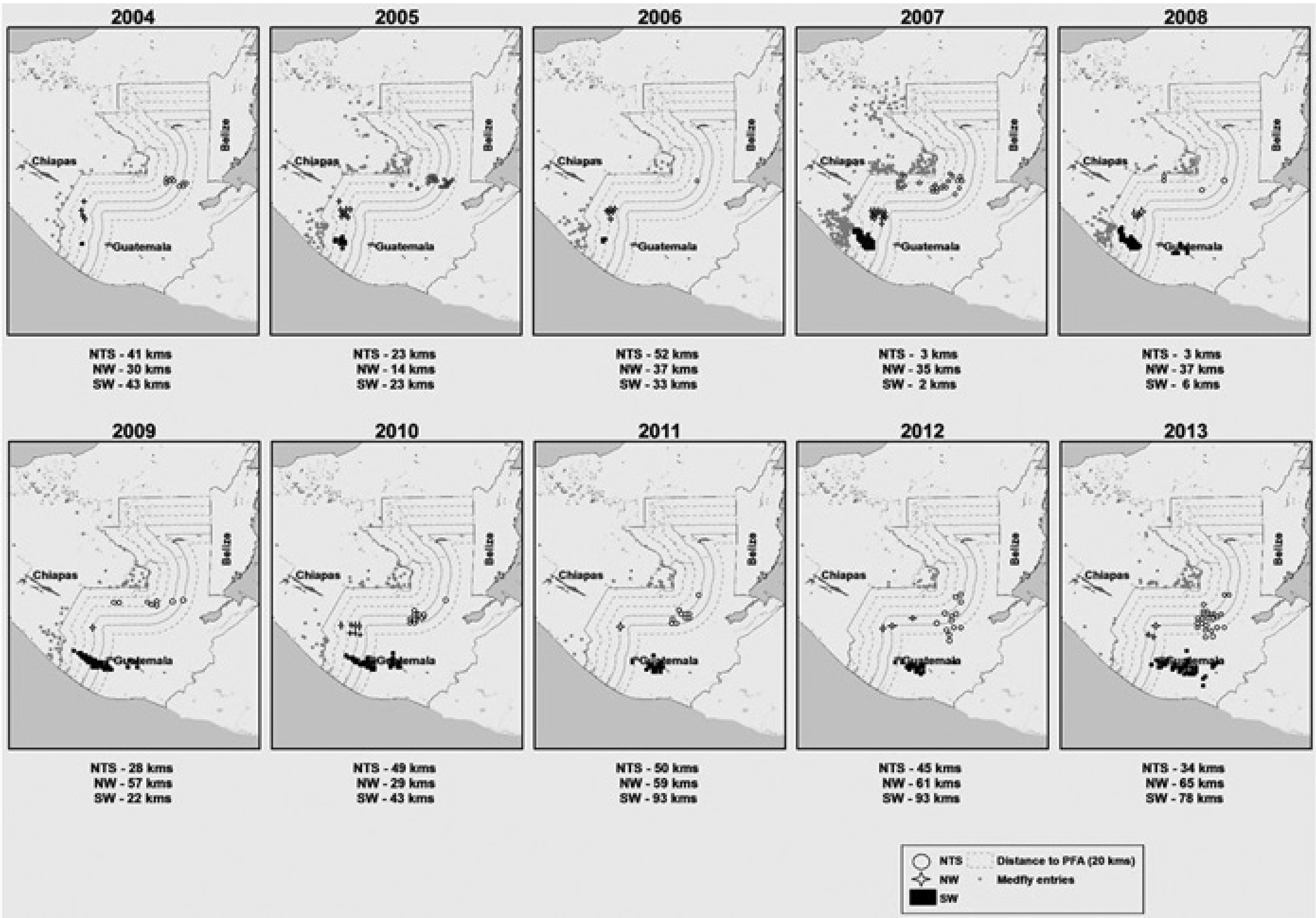


Fig. 3. Location and distance of the leading edge of the Mediterranean fruit fly infestation for the 3 infestation fronts: North Transversal Strip - Marques de Comillas (NTS), Northwest-Comalapa (NW) and Southwest-Soconusco (SW)) in relation to the limits of the pest free areas (PFA) in Chiapas, Mexico for the years 2004-2013. The contour lines of are equidistant 20 km apart and are used as a reference of the distance between the leading edge of the infestation and the limits of the PFA.

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/km^2 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

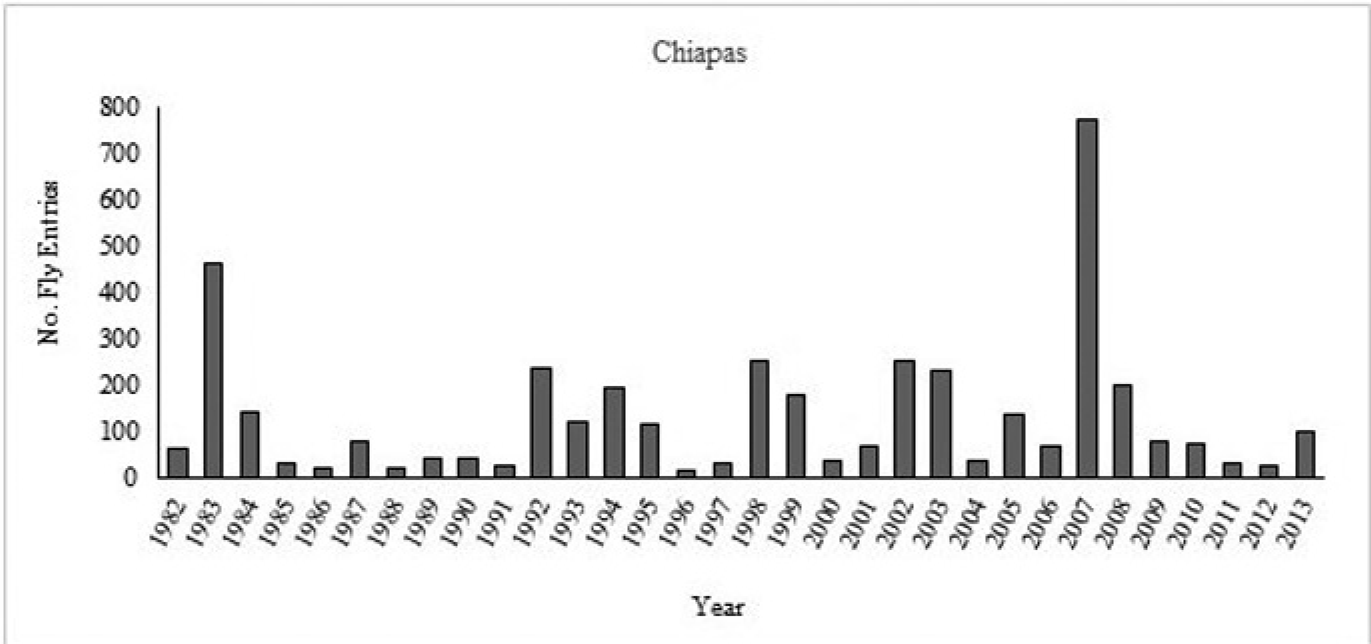
The trapping data produced by the Moscamed Program from 1982 to 2013 (31 years) were used to assess the general trend of medfly entries into the PFA of Chiapas and Tabasco. These data were transformed to average FTD and used as input information in a GIS (IAEA 2003, 2006) to assess the medfly spatial 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



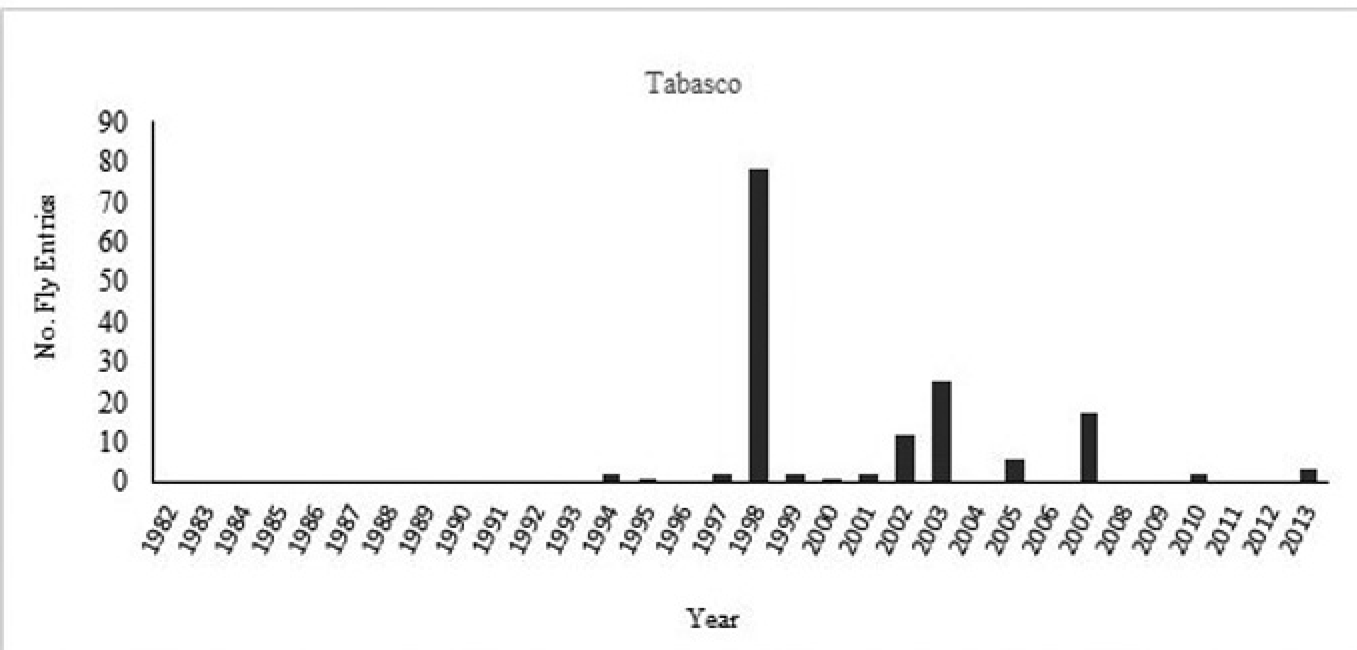


Fig. 4. Number of Mediterranean fruit fly transient entries (detections and outbreaks) in the Mexican States of Chiapas and Tabasco during 1982 - 2013.

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

Fig. 5. Location and percentage of Mediterranean fruit fly transient entries into Mexico during 1982-2013.

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-

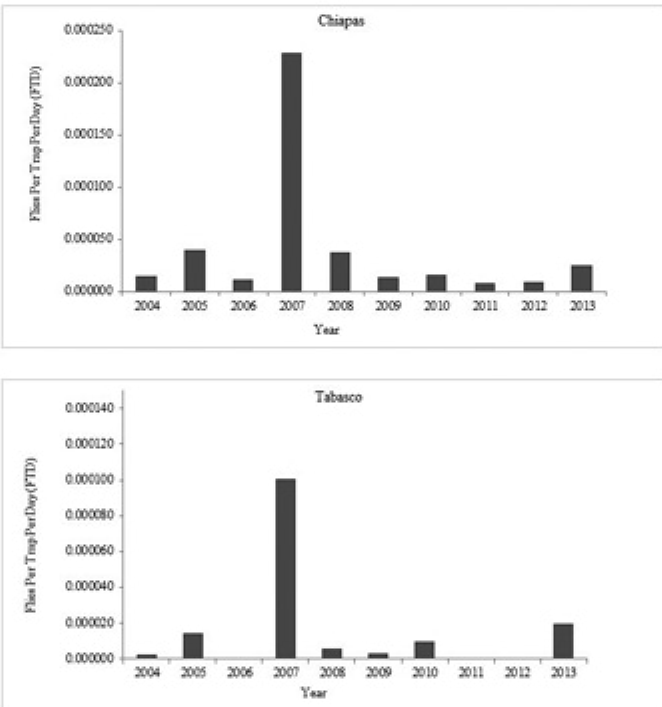


Fig. 6. Mediterranean fruit fly average FTD (flies per trap per day) index in the Mexican States of Chiapas and Tabasco from 2004 to 2013.

grants from Central America travelling north seeking job opportunities in Mexico and the USA. Fruit was also carried in small commercial volumes to be sold at local markets located in the communities along the border between Guatemala and Chiapas. Movement of the infested fruit by agricultural workers and by merchants to the markets at border communities resulted in short distance transient entries of the pest, whereas, movement of infested fruit by migrants resulted in longer distance entries. This was documented in a study conducted by the Moscamed Program from 2006 to 2008 in which the amounts of inspected vehicles, persons (agricultural workers, migrants, tourists, etc.), luggage and confiscated host fruit passing across internal and international border quarantine checkpoints in Chiapas were recorded. The annual average numbers of inspected vehicles, persons and luggage passing across 14 quarantine checkpoints strategically placed along the border of Mexico and Guatemala were 394,545, 641,325 and 801,292, respectively. A total of 9,849 kg of host fruits were confiscated (Moscamed Program internal report Oct 2008). Movement of the pest within fruit from infested areas in Guatemala to 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).

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 to protect the PFA in the region of Marques de Comillas indicated substantial amounts of infested host fruits were carried to the PFA by people (including agricultural workers and merchants) moving from infested areas in the interior of Guatemala to rural communities located along border and into the PFA in northern Chiapas and Tabasco. This suggested that one other independent variable associated with the number of medfly transient entries into the PFA could have been the movement of the pest within infested fruit. In this case, data showed that, based on this inverse relationship, when the leading edge of the infestation was 41 km or more from the limits of the PFA, the average number of medfly transient entries (detections and outbreaks) into the PFA of Marques de Comillas was 25 per year. When the distance decreased to between 41 and 23 km, the expected number of

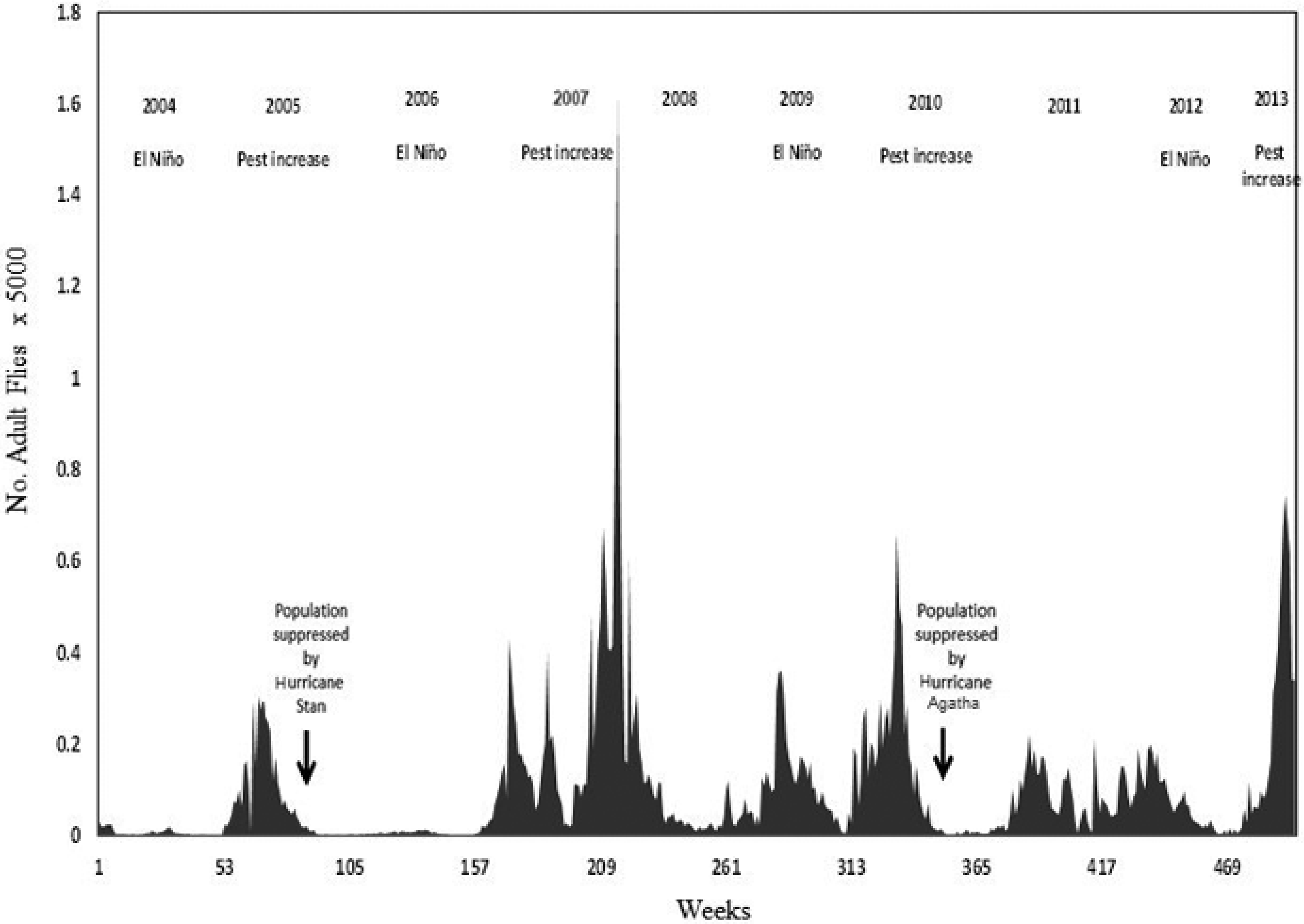


Fig. 7. Mediterranean fruit fly fluctuation (based on routine trapping) within suppression areas in Guatemala associated with El Niño/Southern Oscillation weather events and the population suppression effects of Hurricane Stan and Hurricane Agatha.

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, therefore, 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 upgrading 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 analyzed 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 (Programa 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 reproduction 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 negatively 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

Table 1. Interception of Mediterranean fruit fly larvae (L) in host fruits (KG) confiscated at quarantine checkpoints strategically located in Guatemala to protect the pest free area in Guatemala and in the Mexican border Stat

YEAR	COFFEE		PEACH		PEAR		MANDARIN		SWEET ORANGE		SOUR ORANGE		MANGO		GUAVA		TOTAL	
	KG	L	KG	L	KG	L	KG	L	KG	L	KG	L	KG	L	KG	L	KG	L
2004	223.15	365	970.62	15	7193.09	154	2,138.53	15	10,947.76	0	135.08	2	8,932.09	0	140.93	0	30,681.25	551
2005	371.93	33	1115.15	1412	3452.78	500	2,954.96	17	14,726.22	21	449.08	0	18,701.14	64	277.45	63	42,048.71	2,110
2006	334.25	443	693.64	102	2888.18	77	2,989.31	9	12,886.60	6	231.19	0	12,297.08	0	328.93	19	32,649.18	656
2007	793.41	437	1088.67	754	3111.72	111	3,366.94	82	18,665.35	26	334.28	106	24,135.33	39	398.02	18	51,893.72	1,573
2008	661.75	1,066	1713.74	137	2699.97	574	4,662.55	23	18,591.06	16	384.04	0	15,352.40	2	345.2	4	44,410.71	1,822
2009	1,560.05	184	1604.95	155	1677.7	192	3,769.12	6	12,459.17	0	415.01	0	20,245.58	2	368.03	171	42,099.61	710
2010	998.91	2,044	1209.48	962	1159.02	83	2,740.52	7	11,788.93	10	261.71	95	14,082.80	3	246.36	10	32,487.73	3,214
2011	1,140.98	235	1824.1	45	553.93	0	3,088.06	0	8,853.33	6	381.04	0	19,949.00	0	251.75	10	36,042.19	296
2012	1,466.94	121	759.57	13	643.33	2	2,657.81	5	15,083.87	0	329.77	1	19,848.53	0	169.19	0	40,959.01	142
2013	845.19	31	1336.99	484	416.88	25	1,659.67	0	6,830.79	7	451.18	0	18,033.90	19	255.1	0	29,829.70	566
TOTAL	8,396.56	4,959	12,316.91	4,079	23,796.60	1,718	30,027.47	164	130,833.08	92	3,372.38	204	171,577.85	129	2,780.96	295	383,101.81	11,640

Table 2. Correlations between the distance of the leading edge of Mediterranean fruit fly infestation in Guatemala and pest transient entries into the pest free areas of Soconusco, Marques de Comillas and Comalapa in Chiapas, Mexico, for the years 2004-2013.

Pest Free Area (PFA)	Correlation (Rho)	Significance Level (2-tailed)
Soconusco	-0.939	0.0001
Marques de Comillas	-0.742	0.014
Comalapa	-0.569	0.086

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 F_3, F_4, F_5, F_6 and F_7, 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 km^2 (equivalent to 25 traps/$mile^2$, 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 F_4, and nearly 100% for F_5 to F_7 (Enkerlin 1997; Programa Moscamed 2013a). Lance & Gates (1994) determined through a similar mathematical probabilistic model that 10 Jackson traps baited with TML per 2.59 km^2 (10 traps/$mile^2$) 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 km^2 (5 traps/$mile^2$) 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 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 (Liebhold & 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 km^2 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-

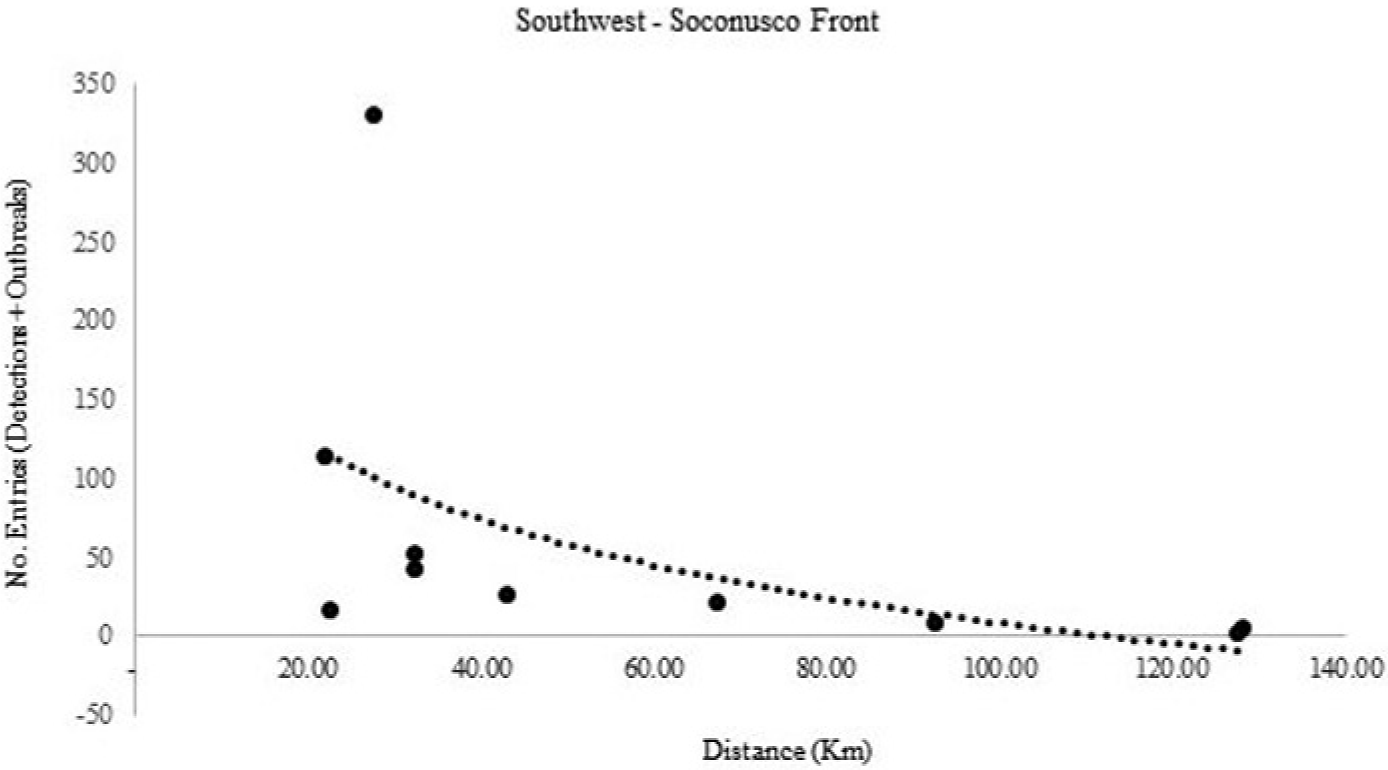


Fig. 8. Relationship between the distance of the leading edge of the medfly infestation in Guatemala and the number of medfly transient entries (detections and outbreaks) into the PFA of Soconusco, Chiapas, for the Southwest–Soconusco (SW) Front for years the 2004-2013.

yond 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 phytsosanitary 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

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.

	SOCONUSCO		MARQUES DE COMILLAS		COMALAPA	
YEAR	No. entries (detections + outbreaks)	Distance to leading edge (km)[1]	No. entries (detections + outbreaks)	Distance to leading edge (km)[1]	No. entries (detections + outbreaks)	Distance to leading edge (km)[1]
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

[1]Distance between leading edge of the Mediterranean fruit fly infestation in Guatemala and the PFA in Chiapas.

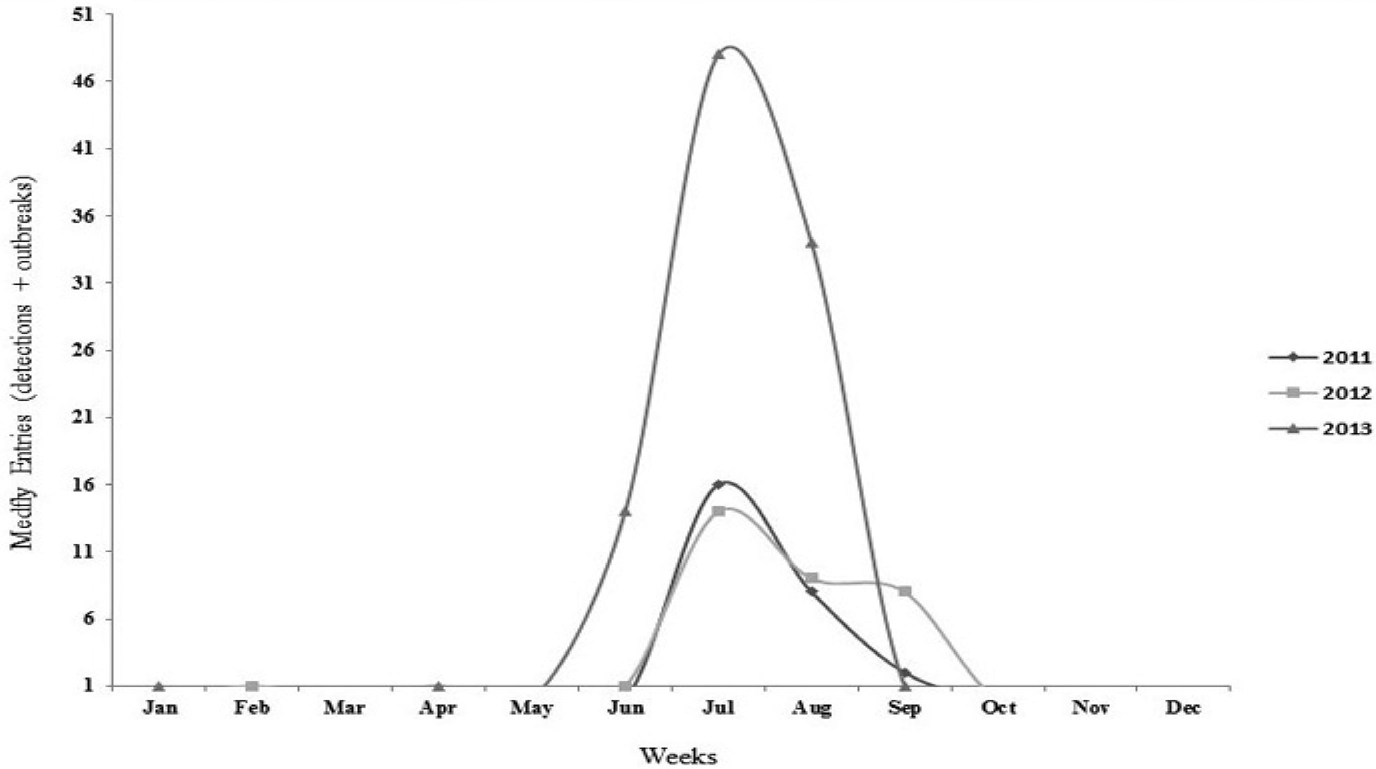


Fig. 9. Numbers of Mediterranean fruit fly transient entries (detections and outbreaks) per month during the years 2011-2013 into the PFA of Marques de Comillas, Chiapas, for the North Transversal Strip–Marques de Comillas (NTS) front.

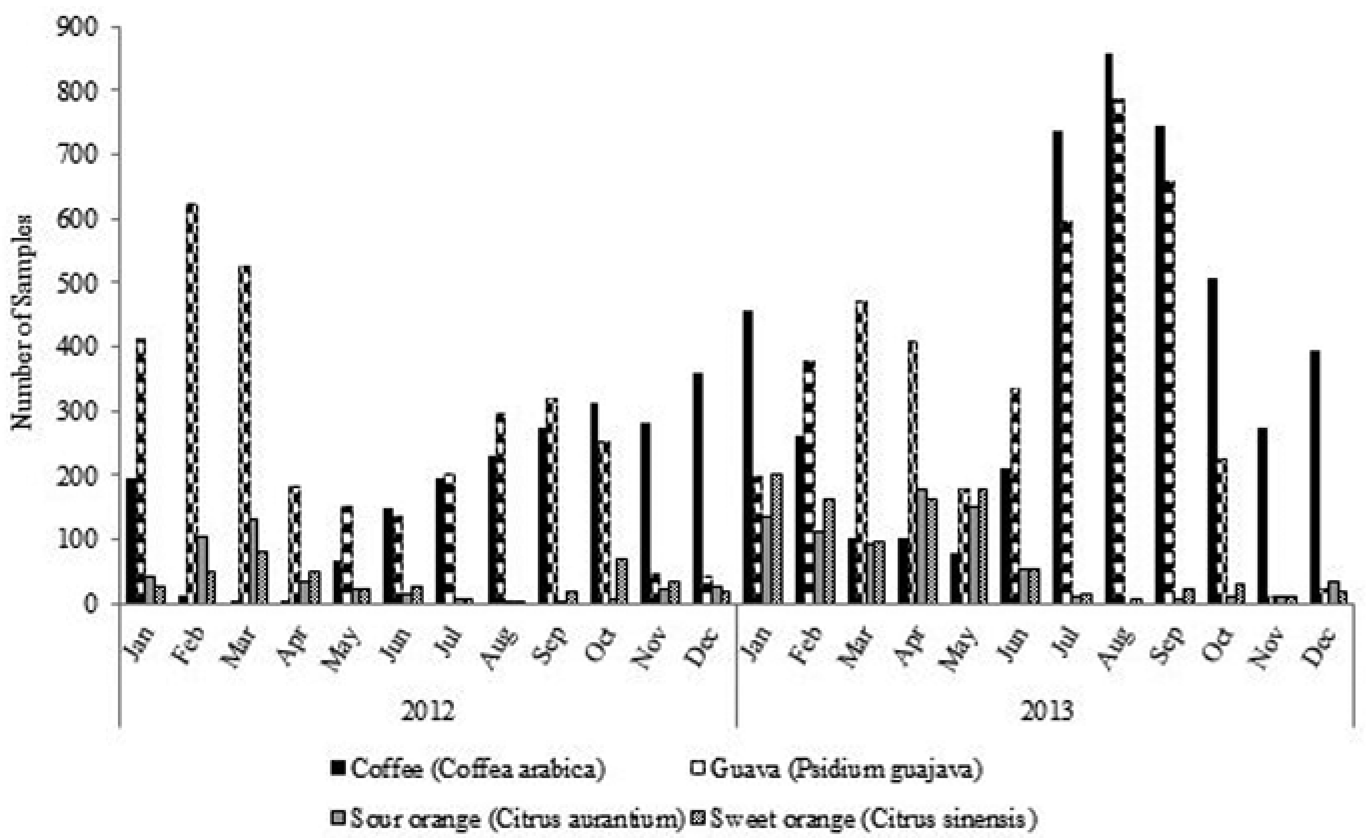
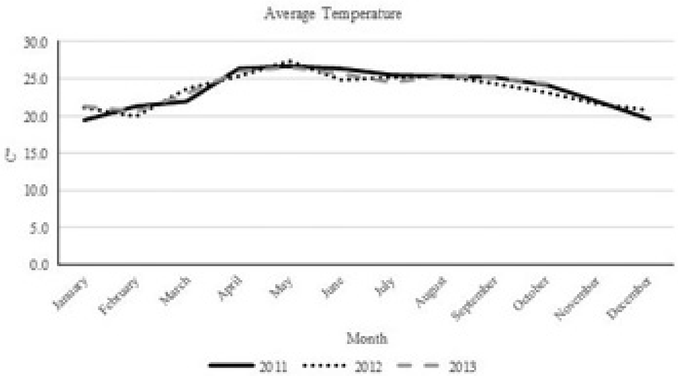


Fig. 10. Number of fruit samples collected during 2012 and 2013 in the Marques de Comillas PFA in Chiapas, Mexico, reflecting availability of Mediterranean fruit fly hosts and fruit phenology in this region.



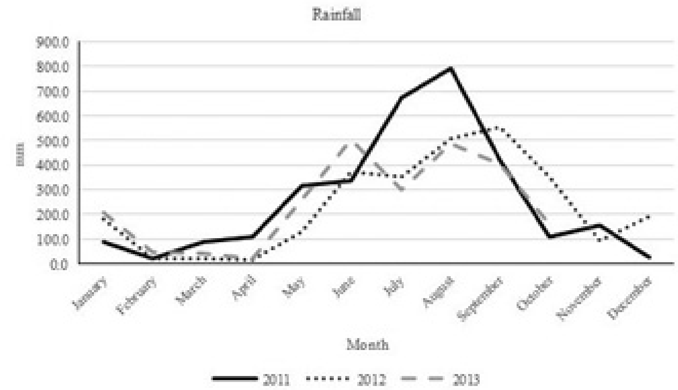


Fig. 11. Average monthly temperatures (°C) and monthly rainfall totals (mm) in the region of Marques de Comillas, Chiapas, Mexico, for the years 2011, 2012 and 2013.

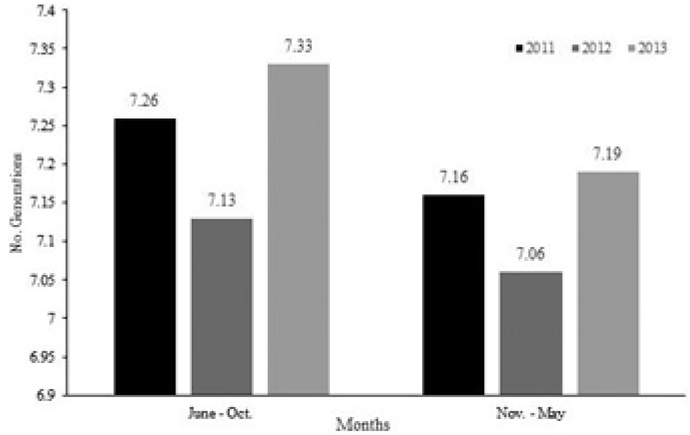


Fig. 12. Number of potential generations of the Mediterranean fruit fly in the Marques de Comillas pest free area (PFA) estimated for the periods Jun to Oct and Nov to May for the years 2011-2013 based on the Tassan degree-day model (Tassan et al. 1982).

positive economic return. The benefit-cost ratio for Mexico over this time period was 112 to 1, clearly indicating that the Mexican Government 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 exports, created jobs in the rural areas and improved the nutrition of the human population by expanding fruit and vegetable supply and consumption 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 throughout the country was an estimated 1.63 million (IICA 2009). There were other benefits such as avoiding the cost of significantly increased insecticide use over more than 30 years in Mexico's horticultural production had the medfly's northward advance not been stopped. Preventing 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 annually. Additional side benefits of the Moscamed Program included the strengthened Mexican plant protection capacity and biocontrol infrastructure. The program has generated spin-offs such as the Moscafrut Program, also integrating the release of sterile insects, which has succeeded 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 surveillance based on regular servicing 24,760 medfly traps (14,710 in Chiapas and 10,050 in the rest of Mexico) country-wide confirming continued 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 (F_1)	Third (F_2)
2010	70	59	10	1	100	0	0
2011	30	27	3	0	97	0	3
2012	24	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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