SUCCESSFUL AREA-WIDE PROGRAMME THAT ERADICATED OUTBREAKS OF THE INVASIVE CACTUS MOTH IN MEXICO

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SUMMARY

The spectacular success of the cactus moth, *Cactoblastis cactorum* (Berg), in controlling invasive *Opuntia* species has been cited often in biological control literature. This insect is highly damaging to plants of the Cactaceae family and has been regarded as one of the most successful classical weed biological control agents. In Australia, the cactus moth effectively controlled approximately 25 million hectares of non-native *Opuntia* species that had invaded cattle grazing lands. In Mexico, however, the Cactaceae are native, where they have their greatest diversity, and have major ecological and socio-economic importance. In the 1950s,

the cactus moth was introduced into several Caribbean islands for management of *Opuntia* spp. on grazing lands. The moth arrived accidentally in Florida by 1989, and concerns were raised that this highly mobile moth could spread into the south-western USA and reach Mexico. Therefore, a cactus moth surveillance programme was established in Mexico in 2002 to detect and prevent the introduction and establishment of this invasive pest. Through this detection trapping network, two localized but large outbreaks of *C. cactorum* were detected off the coast of the Peninsula of Yucatán, Mexico; on Isla Mujeres, 10 August 2006, and Isla Contoy, 4 May 2007, both in the municipality of Isla Mujeres in the state of Quintana Roo. An eradication programme was immediately implemented by the National Service for Health, Safety and Food Quality (SENASICA) of the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) of Mexico, in close collaboration with other national and international organizations. An area-wide integrated pest management (AW-IPM) approach was implemented that included regulatory actions, outreach activities, surveillance, intensive sanitation and the release of sterile moths. Eradication was achieved in 2008 and officially declared in 2009. A surveillance network is currently maintained for detecting early pest incursions, allowing for a rapid response to any future incursion of the pest. This successful programme has resulted in the protection of the high value commercial *Opuntia* cacti industry in Mexico, as well as native *Opuntia* species in natural arid and semi-arid ecosystems where they are an essential element in maintaining biodiversity and soil conservation.

Key Words: *Opuntia*, prickly pear cactus, *Cactoblastis cactorum*, Sterile Insect Technique, sterile moths, biological control, AW-IPM, Yucatán, Quintana Roo

1. INTRODUCTION

In general, biological control is the use of one organism to reduce the population density of another organism. Biological control has been used by humans for about two millennia and has become widely used in pest management programmes since the end of the nineteenth century (DeBach 1964; van Lenteren and Godfray 2005). Classical biological control involves the introduction of a host-specific, non-native natural enemy adapted to a non-native organism that became a pest in its new homeland. Classical weed biological control implies the importation of natural enemies to control a non-native weed species.

The South American cactus moth, *Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae), is a well-known example demonstrating the great success that can be achieved using plant-feeding insects as classical biological control agents of invasive plants (Dodd 1940; Pettey 1948; Zimmermann et al. 2004). The removal of highly invasive species of prickly pear cacti (*Opuntia* spp.) from millions of hectares (ha) of Australian farmland, rangeland, and natural habitat was a great early success in biological control of weeds. The dramatic “before and after” pictures of devastated dense cactus vegetation after releasing *C. cactorum* (Dodd 1940) are familiar examples of the stunning impact of successful classical biological weed control (DeBach et al. 1976).

Several programmes resulted in successes similar to the programme in Australia, including South Africa and Hawaii (Zimmermann et al. 2000, 2004). However, in 1956 the decision was made to release *C. cactorum* on the Caribbean island of Nevis, part of the Leeward Islands group of the West Indies, where *Opuntia* species occurred

that were native. Control of *Opuntia* on Nevis Island was deemed important to help manage a complex of native prickly pears dominated by *Opuntia triacantha* (Willdenow) and introduced species that were considered a serious weed pest in overgrazed rangeland where they outcompeted grasses and caused injury to livestock and animal handlers (Simmonds and Bennett 1966). Three species of natural enemies, including *C. cactorum*, were shipped from South Africa and released on Nevis Island in early 1957. *C. cactorum* was apparently the only natural enemy that became established, spreading rapidly and causing the collapse of prickly pear populations on the island. This biological control programme was considered “outstandingly successful” (Simmonds and Bennett 1966).

Based upon these successes, *C. cactorum* was introduced on the islands of Montserrat and Antigua in 1960, where it also became established and caused substantial reduction of native prickly pear populations (Simmonds and Bennett 1966). Thereafter, *C. cactorum* continued spreading, either naturally or with intentional or unintentional human involvement, through many regions of the Caribbean, including Puerto Rico, the U.S. Virgin Islands, the Dominican Republic, the Bahamas, and Cuba, where it attacked native *Opuntia* spp. (Zimmermann et al. 2000).

In 1989, *C. cactorum* was discovered on native *Opuntia* spp. in southern Florida, USA (Habeck and Bennett 1990; Dickel 1991) and received considerable attention in view of its potential negative ecological and economic impact in the southern and western USA (Simberloff et al. 1996). How the moth arrived in Florida is unclear. The moth may have arrived through natural dispersal by flight, possibly storm-aided, since the moth was established in Cuba, only 128 km from the Florida Keys (Zimmermann et al. 2000). Perhaps the most compelling explanation for the expansion of *C. cactorum* was proposed by Pemberton (1995), who suggested that the moth may have been unintentionally introduced through commerce of ornamental cactus. During the 1980s, 300,000 *Opuntia* plants destined for nursery sales were shipped from the Dominican Republic to Miami every year. From 1981-1986, *C. cactorum* was intercepted 13 times at Miami ports, including larvae found in stems of *Opuntia* plants from the Dominican Republic (Pemberton 1995).

Molecular genetic analysis of *C. cactorum* specimens from Florida also supports the hypothesis that multiple introductions into Florida occurred from a location outside the insects’ native range in South America (Simonsen et al. 2008; Marsico et al. 2011).

Thus *C. cactorum* had become an invasive species with a high biotic potential. Although the moth is not a typical long-distance flyer, with a maximum recorded dispersal distance of 24 km (S. D. Hight unpublished data), it has a high reproductive capacity with egg sticks usually consisting of 70-90 eggs, sometimes up to 120 eggs, and a female that produces three or four egg sticks during her lifetime (Zimmermann et al. 2004). “*A worm that turned*” is the title of a popular article that describes the threat of the same “miracle” insect when its host plants were no longer considered weeds, but native cacti of great economic, ecological and aesthetic value (Stiling 2000).

Over a period of 20 years, this invasive moth has been spreading from southern Florida as far north as central coastal South Carolina and as far west as coastal Louisiana (Hight et al. 2002; Hight and Carpenter 2009). In 2017, the moth was found in southern North Carolina, approximately 160 km from the last known location of *C. cactorum* in South Carolina (Jarred Driscoll, North Carolina Department of Agriculture, personal communication).

In view of this threat, already in 2002, Mexico initiated a surveillance campaign for *C. cactorum* under the *National Preventive Campaign against Cactus Moth*, with the purpose of early detection of any incursion. This surveillance network detected two outbreaks of *C. cactorum* in the state of Quintana Roo, Yucatán Peninsula, i.e. on 10 August 2006 on Isla Mujeres and on 4 May 2007 on Isla Contoy, both within the municipality of Isla Mujeres (Hight and Carpenter 2009) (Fig. 1).

Also because of concerns of the growing threat to native and cultivated *Opuntia* species with the continued spread of the cactus moth, the USA and Mexico developed a *Bi-National Cactus Moth Programme* in 2006 that was implemented with funding from both countries. Operations supported by the Bi-National Cactus Moth Programme were initially directed at suppressing populations and containing the leading edge of the infestation in the USA along the Gulf Coast of Florida, Alabama, and Mississippi (Bloem et al. 2007; Carpenter et al. 2008). When the two outbreaks occurred in Quintana Roo in 2006, the Bi-National Programme also supported eradication efforts in Mexico.

In this paper we describe the development of a surveillance and eradication programme that was implemented by the Government of Mexico in close collaboration with the USA and with other national and international organizations.

2. THE IMPORTANCE OF *OPUNTIA* CACTI IN MEXICO

The genus *Opuntia* is one of the most widely used plants in Mexico and Central America. Due to the high protein and fibre content in the stems, or pads, and the amount of water in their tissue (88-91%, Pimienta-Barrios 1990). *Opuntia* cacti have an extremely wide range of uses, from human and animal food to cosmetics and adhesives (Barbera 1995). In Mexico, traditional uses of *Opuntia* vary widely although there are two main products that account for the economic importance of *Opuntia* products: food and fodder (Pimienta-Barrios 1990; Barbera 1995).

Fodder is mainly for cattle and goats in all parts of Mexico, but its use for forage has been documented in many other parts of the world including the USA, northern and southern Africa, and several South American countries (Felker 1995). In Brazil, for example, close to 300 000 ha has been planted with *Opuntia* cacti to produce fodder for livestock (Barbera 1995). *Opuntia* spp. have been cultivated worldwide because of the value of the plants as ornamental and agricultural commodities, and their ability to adapt to various climatic conditions, particularly to semi-arid and arid areas (Hanselka and Paschal 1989).

Opuntia spp., which have been important cultural and agricultural plants in Mesoamerica since the pre-Hispanic era (Zimmermann and Pérez-Sandi-Cuen 2006), annually generate over 300 000 tons of fruit and vegetables in Mexico, and are cultivated on more than 70 000 ha (Pimienta-Barrios 1990; Flores-Valdez et al. 1995; Soberón et al. 2001). As food, *Opuntia* can be consumed as a vegetable (by dicing young pads – “nopalitos”) or as a fruit (tuna or cactus pear). The fruits are produced in 15 out of 32 Mexican states employing close to 20 000 people, whereas vegetables are produced in 14 states and employ close to 8 000 people. In addition, most rural people consume prickly pear from local wild *Opuntia* populations and family-owned plantations maintained at various sizes. The average income generated by *Opuntia* products over the period 1990-1998 is approximately 50 million USD per year, with vegetable usage constituting more than half of the value (USD 27 million), followed by cactus pears (USD 20 million), and finally fodder (USD 1 million). In addition, the export market of *Opuntia* products is valued at USD 50 million per year. Exports are mainly to the U.S., Canada, Europe, and Japan (Soberón et al. 2001). If *C. cactorum* were to establish in Mexico, ca. 30 000 producers of cactus fruit and vegetable would be affected, as well as the nopal processing industries.

Mexico is recognized as the origin of the genus *Opuntia* (Esparza et al. 2004) and has the highest number of cultivated species and varieties of prickly pear in the world (19 cultivated types in total) (Flores-Valdez and Gallegos 1993). Mexico also has one of the highest diversity of species of the genus *Opuntia* (in addition to Cactaceae biodiversity of ca. 560 species) that cover an area of close to 3 000 000 ha (1.5% of Mexican territory). The actual number of *Opuntia* species varies in the literature, partially because of frequent hybridization between species and the lack of a standardized taxonomic classification. Bravo-Hollis (1978) recognized 104 species of *Opuntia* in Mexico, 56 of which are in the subgenus *Platyopuntia* (prickly pears), 38 of which are endemic. From an ecological point of view, loss of acreage covered by *Opuntia* species would accelerate soil loss in arid and semi-arid areas, and the loss of ecological niches to a variety of organisms (Ojeda 2004).

3. FIRST DETECTION IN MEXICO

The two *C. cactorum* outbreak sites (Isla Mujeres and Isla Contoy) were located in the state of Quintana Roo, one of the 32 states of Mexico. This state is part of the Yucatán Peninsula in the south-eastern part of the country, bordering to the north with the state of Yucatán and the Gulf of Mexico, to the east with the Caribbean Sea, to the south with Belize, and to the west with the state of Campeche. Its capital is Chetumal and its most populous city is Cancún.

First outbreak site: Isla Mujeres is a small island located in the Caribbean Sea, 13 km off the coast of the Yucatán Peninsula (Fig. 1). The island is 7 km long and on average 1 km wide (for a total of 455 ha), and it is part of one of the eleven municipalities in the state of Quintana Roo. The municipality of Isla Mujeres, which

includes a part of continental territory, is located 13 km from the city of Cancún, the main tourist attraction in the region. Isla Mujeres has a permanent settlement of approximately 16 000 inhabitants whose primary livelihood is to support the tourist industry. The island is accessed from Cancún by vehicle and passenger ferryboats. Delimiting trapping revealed that the size of the outbreak area was 45 ha infested with moth populations following the spatial distribution of its *Opuntia* hosts scattered over much of the island but concentrated on the southern end.

Figure 1. Location of Isla Mujeres and Isla Contoy near Cancún, Quintana Roo, in the Caribbean Sea, where populations of *Cactoblastis cactorum* were detected, but were later eradicated.

Second outbreak site: Isla Contoy (Fig. 1) is an even smaller island, also belonging to the municipality of Isla Mujeres and located 30 km north of Isla Mujeres. The island is 8.75 km long, and on average 0.5 km wide, and has a surface area of 317 ha. In 1961, the Mexican government declared the island a protected area and a bird sanctuary, and in 1998, it was declared a national park. The island is known as "The Island of the Birds" due to the large numbers of frigate birds and other oceanic avian species that use Isla Contoy as a nesting location.

To the south of the island is the Ixlaché reef that is part of the second largest barrier reef in the world. The National Park Service maintains a small visitor's centre and housing for visiting researchers on the island. Access by tourists to the island is controlled and monitored by the National Park Service. Delimiting trapping revealed that the size of the outbreak area was 3 ha with the moth population somewhat limited to dense stands of *Opuntia* host plants in the central part of the island.

4. FORMATION OF OPERATIONAL PROGRAMME

A number of national and international institutions and organizations joined efforts in the fight against these cactus moth outbreaks. These included: The Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), the United States Department of Agriculture (USDA), the North American Plant Protection Organization (NAPPO), and the Mexican Government through the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA), the National Service for Health, Safety and Food Quality (SENASICA) and the National Forestry Commission (CONAFOR). Technical and economic support was provided to research and development (R&D) and to the implementation of an area-wide eradication programme.

5. RESEARCH AND DEVELOPMENT

The necessary tools for implementation of the eradication programme were developed through effective research and development. These included: determination of the moth's mating behaviours (Hight et al. 2003), design and evaluation of trapping systems (Bloem et al. 2005a), pheromone identification and synthesis (Heath et al. 2006; Cibrián-Tovar 2009; Cibrián-Tovar et al. 2017), population ecology studies including dispersal (Hight et al. 2002; Bloem et al. 2005a; Sarvary et al. 2008), studies on biology of the pest (McLean et al. 2006), implementation of trials to assess susceptibility to insecticides (Bloem et al. 2005b), development of an artificial diet and mass-rearing tools (Marti and Carpenter 2008; Carpenter and Hight 2012), assessment of the feasibility of biological control (Paraiso et al. 2012) and the Sterile Insect Technique (SIT) (Carpenter et al. 2001; Hight et al. 2005), and assessment of the potential economic, social, and environmental impacts of *C. cactorum* both in the USA and in Mexico (Zimmermann et al. 2004; Simonson et al. 2005; Sánchez et al. 2007).

One of the essential tools that was developed and validated was the trapping system based on a standard (unpainted) wing trap (Bloem et al. 2005a), placed at a height of 2.0 m above ground, and baited with a rubber septum impregnated with a synthetic female sex pheromone (Heath et al. 2006). Support from the Joint FAO/IAEA Division was essential for transferring the tools for implementing an AW-IPM approach integrating the SIT (Dyck et al. 2021).

6. PROGRAMME OPERATIONS

The Mexican Government provided the necessary financial resources for programme operations aimed at eradicating the outbreaks on Islas Mujeres and Contoy. The financial resources to support programme implementation are summarized in Table 1. It is important to point out that when the pest was first detected in Mexico, resources were immediately allocated through the declaration of a National Emergency, which is an instrument of Mexican legislation that allows for timely response to this type of phytosanitary emergency.

To raise awareness of the potential impact of the presence of the cactus moth, the following sectors were alerted and informed: Political and administrative government offices and divisions, academic research and technical institutions, industry stakeholders, commercial agricultural enterprises, natural area managers, growers, farmers and ranchers, non-government agencies, amusement parks, hotels in tourist areas, and the public in general. It was also essential to carry out the necessary feasibility assessments and to support the preparation of public outreach materials such as booklets, videos, and calendars.

Table 1. Total financial resources (USD) made available from 2006 through 2010 for the implementation of cactus moth eradication programme activities by the Mexican Government through the National Service for Health, Safety and Food Quality (SENASICA) and the National Forestry Commission (CONAFOR)

Year	Contribution from SENASICA	Contribution from CONAFOR	Total
2006	192 926	181 818	374 744
2007	1 090 909	0	1 090 909
2008	772 727	34 386	807 114
2009	318 182	0	318 182
2010	240 000	0	240 000
Total	2 614 744	216 205	2 830 949

The cactus moth eradication programme in Mexico followed a similar AW-IPM approach and operational tactics as had been used to suppress and contain the pest in the USA along the Gulf of Mexico. These included: regulatory actions, raising public awareness, extensive surveys, sanitation of infested host plants through mechanical removal as well as removal of egg sticks, and finally the release of sterile moths produced at the USDA insectary in Tifton, Georgia and shipped to Mexico (Table 2). These actions eradicated *C. cactorum* populations in Mexico (Bloem et al. 2007; Hernández et al. 2007; Carpenter et al. 2008; NAPPO 2009; Hight and Carpenter 2016).

Table 2. Actions implemented to eradicate the cactus moth from Isla Mujeres and Isla Contoy

Actions/Activities	Isla Mujeres	Isla Contoy	Rest of the Quintana Roo	Yucatán and Campeche	Rest of the Country
Surveillance					
Trap deployment and weekly trap checks	X	X	X	X	X
Identification of adult captures with differentiation between wild and sterile adults	X	X	X		
Identification of sentinel sites and weekly checking of sentinel plants for egg-sticks oviposited by wild females	X	X			
Review of permanent observation points			X	X	X
Identification of suspect detections in cultivated and wild areas	X	X	X	X	X
Pest Control					
Host plant removal (<i>Opuntia dillenii</i> Ker Gawl, <i>Nopalea cochenillifera</i> (L.) Mill.)	X				
Eggstick removal	X	X			
Application of insecticides	X	X			
Application of herbicides	X				
Sterile moth releases	X	X			
Host census	X	X	X		
Exchange programme with homeowners of ornamental <i>Opuntia</i> plants or voluntary surrender by the inhabitants	X				
Regulation of host mobilization					
Prohibition of the move-ment of <i>Opuntia</i> plants or their parts off or within the island	X	X			
Review of transport in the sea ports	X	X			
Disclosure and training					
Training workshops for staff of programme	X	X	X	X	X
Development and dispersal of informative material	X	X	X	X	X
Radio and television spots to educate the public of the programme and dangers of <i>C. cactorum</i> outbreak	X	X	X	X	X
Meetings with municipal presidencies and local authorities	X	X	X	X	
Meetings with schools, hoteliers and managers of natural parks	X	X	X		
Supervision and evaluation visits with the following groups:					
SAGARPA State Delegation	X	X	X	X	X
Plant Health General Directorate	X	X	X	X	X
Experts from FAO/IAEA	X	X	X	X	
Experts from USDA	X	X	X		
Technical Group Meetings	X	X	X	X	X
Technical reports					
Data collection	X	X	X	X	X
Weekly reports to the Plant Health General Directorate	X	X	X	X	X
Reports to the local authorities	X	X	X		

The SENASICA-SAGARPA national surveillance system allowed early detection of pest incursions, followed immediately by the implementation of delimitation and eradication actions to eliminate the two outbreaks of this invasive species. This prevented further dispersal and introduction of the pest to other uninfested areas. The actions that were implemented to eradicate the cactus moth from Isla Mujeres and Isla Contoy are summarized in Table 2.

7. PROGRAMME RESULTS AND ERADICATION

7.1. Surveillance and Control on Isla Mujeres

Initially 66 traps were deployed on Isla Mujeres, primarily in and around the infested 45 ha; this was later expanded to a total of 115 traps. Trapping and host plant sampling and removal soon revealed high infestation levels throughout the island with thousands of egg sticks and larvae collected and destroyed and adult males trapped (Fig. 2). The effect of the rapid and aggressive response from SENASICA personnel was visible almost immediately, and the density of the outbreak population of *C. cactorum* was quickly reduced. A total of 4126 egg sticks were collected from plants during the eradication effort and 321 adult males were trapped.

Figure 2. Larvae and egg sticks of *Cactoblastis cactorum* collected on Isla Mujeres during the initial stages of the eradication programme.

Once trapping efforts revealed a dispersed infestation over much of the island, removal of above-ground host plant material was conducted to suppress additional *C. cactorum* population increase. As part of the mechanical control, 240 tons of potential and infested host plants were removed throughout the island. Only 27 sentinel host plants remained, which were plants that were easy to access and could be checked daily for the presence of egg sticks or damage caused by the larvae.

Two censuses for *Opuntia* spp. host plants were carried out in the backyards of homes throughout the island in March and June 2008. A total of 3050 sites with susceptible host plants were identified in private homes, public offices, hotels, and vacant lots. To facilitate the removal of host plants, a protocol was implemented to replace each host plant with a non-host ornamental plant, mainly species of palms (1140 specimens) and magueys (*Agave* spp.) (74 specimens). CONAFOR kindly provided the replacement plants for this part of the programme.

The population trend of *C. cactorum* on Isla Mujeres is indicated by the weekly total number of egg sticks collected (Fig. 3) and weekly total number of wild males caught (Fig. 4). A drastic reduction in the cactus moth population resulted from the intensive mechanical control and adult mass-trapping. This prepared the ground for the integration of the SIT on an area-wide basis and assured a competitive sterile to wild insect ratio. The targeted initial overflooding ratio was 10 sterile to 1 wild moths as identified in trap captures. In preparation for sterile moth releases, extensive quality control, flight ability, and dispersion tests had been conducted, and shipping techniques evaluated in the USA.

Figure 3. Total *C. cactorum* egg sticks collected from *Opuntia* spp. plants each week from August 2006 to March 2007 on Isla Mujeres. Collections were concentrated in an area of 45 ha in the southern end of the island's 455 ha.

Figure 4. Total wild *C. cactorum* male moths caught weekly in pheromone-baited traps from October 2006 to March 2007 on Isla Mujeres. Captures were concentrated in an area of 45 ha in the southern end of the island's 455 ha.

The first trial of sterile adult moth releases ($n = 1398$) was carried out on Isla Mujeres on 1 November 2007; it primarily targeted to the area where the last egg sticks were collected and the last male *C. cactorum* were captured. Release time frame for packages of shipped sterile moths was within 48 hr; from insect packaging, delivery to a USA airport, receipt in Cancún, to release on Isla Contoy.

Given the fact that the last wild individuals were detected during the second week of March 2007 (Fig. 3), it is possible that during the time the sterile moths were released, eradication may have already been achieved. Nevertheless, application of the SIT gave assurance that no remnant of the invasive population of the cactus moth remained.

7.2. Surveillance and Control on Isla Contoy

After detection of the cactus moth on 4 May 2007, programme activities were immediately intensified on Isla Contoy. This however, required the processing of access permits, as the island is a protected natural reserve and the cactus vegetation could not be mechanically removed as it was on Isla Mujeres.

A total of 44 traps were deployed and the trap catches indicated that the outbreak was limited to the central part of the island. All larvae found ($n = 1028$) as well as all damaged plant parts ($n = 122$) were removed. Some wild cactus plants exhibited damage caused by another cactophagous moth, presumably of the genus *Melitara*, which made it difficult to differentiate the damage from that of the cactus moth.

A total of 46 *C. cactorum* egg sticks were collected on Isla Contoy (Fig. 5) and a total of 41 wild male adult cactus moths were caught in the traps (Fig. 6).

The first trial release of sterile adult moths ($n=1281$) was carried out on Isla Contoy on November 7, 2007. After this release, 18 sterile adults were caught in the traps (confirmed in the laboratory), suggesting that the dispersal behaviour and competitiveness of the sterile insects was adequate.

Figure 5. Total *C. cactorum* egg sticks collected weekly from *Opuntia* spp. host plants from May 2007 to February 2008 on Isla Contoy. Collections were concentrated in an area of 3 ha of the island's 317 ha.

Figure 6. Total wild *C. cactorum* male moths caught weekly in pheromone-baited traps from March 2007 to February 2008 on Isla Contoy. Captures were concentrated in an area of 3 ha of the island's 317 ha.

The last wild moth was captured in January 24, 2008. After conducting various field release tests, the programme carried out continued weekly releases of sterile moths, considering the biological conditions of the pest and the availability of sterile insects, from March 1, 2008 until July 2, 2008. For both islands a total of 21 398 sterile moths were released, of which 75% were males.

Weekly releases of sterile moths during 4 consecutive months assured complete eradication of possible remnant *C. cactorum* populations. The sterile moths, reared and sterilized at the USDA-Agricultural Research Service (ARS) laboratory in Tifton, Georgia, were packaged in Petri dishes and shipped by commercial air cargo in insulated cardboard wrapped Styrofoam shipping boxes (KoolTemp™ GTS-89 Shipping System, Cold Chain Technologies, Holliston, Massachusetts). Hight and Carpenter (2016) provide additional packaging details. Refrigerant Kool Guard II cooling bricks were included in the containers to maintain a targeted temperature around the sterile insects of 1–4°C.

7.3. Additional Programme Activities

Between January 6 and February 3, 2007, 6 wild adult cactus moths were caught in traps deployed in the continental area of Cancún, on the Quintana Roo mainland. In response, activities were immediately intensified on the mainland adjacent to Isla Mujeres and Isla Contoy. Three thousand additional traps were deployed and distributed among houses, hotels and shops in the coastal area covering a total area of 22.2 km². Wild host plants were examined in the vicinity of Nichupte Lagoon for possible detection of egg sticks or larvae. No further positive moth captures were reported after February 3, 2007, and no egg sticks were found on mainland Quintana Roo.

In the state of Quintana Roo, a trapping network was maintained with a total of 262 traps and 729 Permanent Observation Points (POPs) with *Opuntia* host plants present. In the neighbouring state of Yucatán (from El Cuyo to Celestun), 130 traps were deployed and 122 POPs were monitored; and in Campeche state (Rio Verde, Real de Salinas and Jaina) 79 traps were deployed and 50 POPs monitored. Traps and POPs were checked weekly and fortnightly, respectively.

Training and raising awareness activities were implemented in support of the programme. They consisted of 3 training courses, 500 radio spots, 700 posters and 4000 flyers distributed on Isla Contoy, 25 000 flyers and banners in English and Spanish, 107 videos in English and Spanish distributed in the area of the Yucatán Peninsula, 6 news broadcasts on local television stations and one on national television.

Since the beginning of the eradication programme (August 2006), 6 experts from the Mexico-USA Bi-National Cooperative Programme and from the FAO/IAEA Joint Division made multiple visits to the programme and provided technical advice.

8. PROGRAMME OUTCOME

In 2009, after a period equivalent to three estimated biological life cycles of the pest without any further detection, the two cactus moth outbreaks were considered eradicated from the state of Quintana Roo, maintaining Mexico free of this pest.

The following Official Agreements were published in the Official Gazette of the Mexican Federation:

- On 26 March 2009. “*Agreement by which the outbreak of cactus moth (Cactoblastis cactorum Berg) was declared eradicated from Isla Mujeres, Municipality of Isla Mujeres, State of Quintana Roo*” (SAGARPA 2009a).
- On 12 October 2009. “*Agreement by which the outbreak of cactus moth (Cactoblastis cactorum Berg) declared eradicated from Isla Contoy, Municipality of Isla Mujeres, State of Quintana Roo*” (SAGARPA 2009b).

Based on the above and in accordance with the International Standard for Phytosanitary Measures No.8 “Determination of pest status in an area” (FAO 2017), the cactus moth was considered eradicated after more than three generations without detections, and continued surveillance since then has confirmed its continuous absence from Mexico.

The National Preventive Campaign against Cactus Moth began in 2002 and continued until 2009, with eradication actions carried out under the coordination of National Plant Protection Directorate.

In 2010, the Phytosanitary Epidemiological Surveillance Programme was created and all surveillance actions against the cactus moth became part of this Programme, under the coordination of the National Phytosanitary Reference Centre. Activities under this Programme have continued and were expanded throughout the country since its creation, for timely detection of any cactus moth incursions. This preventive activity is conducted through exploratory actions, sentinel plots and trapping routes in the areas where *Opuntia* is commercially grown for vegetable, forage and prickly pear production.

From 2010-2017, the federal investment in surveillance activities amounts to more than USD 4.15 million (SAGARPA-SENASICA 2017) (Fig. 7).

To date there are 84 105 field observations/records on the genus *Opuntia* entered into the National Plant Protection Directorate database (SIRVEF 2018). These observations are distributed as follows: 2841 observations at sentinel plots, 65 103 observations for trapping routes (trapping with pheromone), and 11 497 observations on surveillance routes (sentinel plants where the technicians look for larval damage and egg sticks of the cactus moth). The observations/records are established in 842 sentinel plots, 131 surveillance routes, and a national trapping network of 1660 traps, installed in potential strategic risk areas for the establishment of the pest (SAGARPA-SENASICA 2016).

Figure 7. Yearly assigned budget for *Cactoblastis cactorum* preventive surveillance programme in Mexico from 2010 up to 2017.

As a result of these actions under the Phytosanitary Epidemiological Surveillance Programme, to date, no more specimens of the cactus moth have been detected anywhere in the country.

9. FUTURE PERSPECTIVE AND ONGOING SURVEILLANCE

It is almost inevitable that this insect will continue advancing along the USA Gulf Coast, where active containment activities are no longer ongoing. This could result in the pest eventually spreading into Texas and reaching areas adjacent to northeast Mexico, thus posing a constant threat of introduction and invasion of Mexican territory.

Pathway risk analysis has shown that the most likely routes of invasion to Mexico are from Florida including the Keys, along the Gulf Coast states to Texas, and from there to northern Mexico (Simonson et al. 2005). Likewise, Cuba is the closest island to the Caribbean coast of Mexico, and arrival of the cactus moth through this route is very likely due to its proximity with the Yucatán Peninsula, a region with large and wide-spread populations of *Opuntia* cacti (Sánchez et al. 2007).

Due to this permanent pest risk, it is essential to continue the preventive activities through the Phytosanitary Epidemiological Surveillance Programme. Emphasis should be placed on states that are more exposed to cactus moth entries and where *Opuntia* cacti are a valuable commodity.

10. CONCLUSIONS

The cactus moth programme in Mexico is an example of the successful eradication of outbreaks of an invasive pest species integrating the SIT (Hendrichs et al. 2021). The AW-IPM approach was able to combine technical, social, economic, human and political resources to achieve the objective.

Nevertheless, the threat prevails and the Mexican government, under the ongoing preventive Phytosanitary Epidemiological Surveillance Programme, is prepared for the early detection and timely response to a new cactus moth incursion.

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