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CASE STUDY

Maize Pests in Mexico and Challenges for the Adoption of Integrated Pest Management Programs

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ABSTRACT. Mexico is the fifth largest maize producer and the area of origin and domestication of this crop. Mexico's 6.8 million hectare annual production of maize represents 30% of its total domestic agricultural production and 6.6% of the country's arable land. However, Mexico's average yield of 3.17 tons per hectare is 38% below the world's average. Although maize is a major crop globally, it is typically not grown under modern or comprehensive integrated pest management (IPM) programs aimed at minimizing economic damage and lowering environmental and health risks. Pest management in commercial maize in Mexico continues to rely primarily on chemical control using conventional synthetic insecticides. Approximately 3,000 tons of active ingredient per year are used to combat the single most important pest, the fall armyworm (*Spodoptera frugiperda* Smith), followed by the corn earworm (*Helicoverpa zea* Boddie) and the black cutworm (*Agrotis ipsilon* (Hufnagel)). Mexican farmers have successfully adopted IPM programs for many crops, but IPM is not common in maize crops. Although different components and elements have been identified, most of the information on maize pests and IPM in Mexico has been published in technical bulletins of a reduced regional scope or in difficult-to-access reports, generally describing laboratory screenings, preliminary field evaluations, or listing technical recommendations but rarely including products and practices that growers actually use. This report provides up-to-date information on the common pests in the main maize-growing areas of Mexico from experts in the field. Updated information on maize pest population dynamics and control has been gathered from agricultural professionals directly involved in maize crop protection. This critical information, not readably available for Mexican production systems, is intended to help researchers, government officials, and industry specialists in making decisions regarding time and resource allocations in the design and implementation of IPM techniques, practices, and programs for Mexican maize.

RESUMEN. México es el centro de origen y domesticación del maíz y el quinto mayor productor de este grano del mundo, ocupando más de 6% de su superficie arable, lo que representa una tercera parte de su producción agrícola interna. El manejo integrado de plagas (MIP) puede ser una estrategia importante para reducir el daño de plagas y disminuir la cantidad de insecticida que SE usa. El problema de plagas en este cultivo lo encabeza *Spodoptera frugiperda* Smith, el gusano cogollero, para el cual SE utilizan anualmente 3,000 toneladas de ingrediente activo insecticida para su control; al cual le siguen otros lepidópteros como *Agrotis ipsilon* (Hufnagel), gusano trozador, y *Helicoverpa zea* Boddie, gusano elotero, los que en su conjunto SE les aplica insecticida 1–3 veces en cada ciclo de cultivo. Científicos mexicanos han trabajado en diferentes aspectos del MIP en maíz; sin embargo estas tácticas casi nunca son utilizadas por los agricultores mexicanos. Un grupo de científicos y asesores agrícolas en México fue entrevistado para obtener la importancia de las plagas del maíz identificando la presencia temporal y territorial de éstas durante las diferentes etapas de desarrollo del cultivo. Se obtuvo también un inventario de las prácticas de control más usadas, las dosis y frecuencia con las que SE hacen las aplicaciones de insecticida. Esta información, no disponible anteriormente, intenta apoyar a investigadores, funcionarios de gobierno y especialistas de la industria a priorizar esfuerzos y recursos para el diseño e implementación de técnicas, prácticas y programas MIP para la producción de maíz en México.

Key Words: *Spodoptera*, maize production, insecticide use, temporal and geographical pest occurrence

Maize (*Zea mays* L.) is the most widely produced crop in the world (U.S. Department of Agriculture, Foreign Agricultural Service [USDA-FAS] 2013). Mexico, the fifth largest maize producer and area of origin and domestication of this crop (Matsuoka et al. 2002), has planted annually ≈6.8 million hectares in the past 5 yr, representing 30% of its total domestic agricultural production and 6.6% of the country's arable land (Secretariat of agriculture, livestock, rural development, fisheries and food [SAGARPA] 2013, World Bank 2013). However, the country's average yield of 3.17 tons per hectare is 38% below the world's average (USDA-FAS 2013).

Many factors limit maize yield and productivity around the world. Weeds, the main pest problem, reduce yield potential by as much as 11%; animal pests contribute with 10% of the reduction and plant pathogens an additional 11% (Oerke 2006). Although maize is a major crop globally, it is typically not grown under modern or comprehensive integrated pest management (IPM) programs. IPM is a strategy to avoid or minimize economic damage and to lower environmental impact of pest control relative to the indiscriminate use of pesticides. Multiple tools and tactics based on the biology and population ecology of crops and pests, economic feasibility of the crop, and decision and action thresholds, are incorporated into an IPM program (Higley and Pedigo 1996, Kogan 1998, U. S. Environmental Protection Agency [U.S. EPA] 2013). As a reference, in 1986, only 20% of the maize crop area in the United States, the largest producer in the world (U.S. Department of Agriculture, National Agricultural Statistics Service [USDA-NASS] 2013), had adopted this pest control management (Morse and Buhler 1997). The global situation has not changed significantly in recent years especially in Mexico. Approximately 3,000 tons of active ingredient per year are used to combat the fall armyworm (*Spodoptera frugiperda* Smith) (Blanco et al. 2010), the

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most important maize pest in the American continent (Molina-Ochoa et al. 2001, Morillo and Notz 2001, Murúa and Virla 2004, de Melo et al. 2006, Zenner de Polanía et al. 2009). The severity of this pest in maize and lack of IPM program in many important crops has placed Mexico as the country using the highest quantity of pesticides per arable land in North America (Stokstad 2013).

Based on their level of technology adoption, maize production systems in Mexico may be classified as "commercial" maize, usually involving high capital investment and more technology, and "self-consumption" maize, involving high manual labor investment and less technology (SAGARPA 2013). Damaging pest populations occur in all production systems across the country but are mainly managed and controlled in commercial maize, not as much in self-consumption maize. Arthropod pest management in commercial maize relies primarily on chemical control using conventional synthetic insecticides.

Mexican farmers have successfully adopted IPM programs for tomatoes (Trumble and Alvarado-Rodríguez 1993), pecan trees (Rodríguez del Bosque and Tarango-Rivero 1997), broccoli and chili peppers (Blanco 2005), and for fruit flies (Tephritidae) (Mota-Sanchez et al. 2003). Different IPM components including biological control agents have been identified for all major maize pests. These include nearly 40 diseases, predators, and parasitoids of fall armyworm (Molina-Ochoa et al. 2001, Cortez-Mondaca et al. 2012, Estrada-Virgen et al. 2013), nine parasitoids of the leafhopper *Dalbulus* spp. (Moya-Raygoza et al. 2008), 13 parasitoids of the bollworm–tobacco budworm (*Helicoverpa zea–Heliothis virescens*) complex (Loera-Gallardo et al. 2008), and 38 of *Diatraea* spp., and *Eoreuma loftini* (Dyar) borers (Rodríguez del Bosque and Vejar-Cota 2008). Natural enemies are able to keep only 10% or less of *S. frugiperda* populations below the common action threshold of ≥20% of the plants with *S. frugiperda* larvae (Cruz and Turpin 1983, Harrison 1984, Fernández 2002). Control alternatives, such as the use of beneficial nematodes (Molina-Ochoa et al. 1999), bio-rational and low-impact insecticides (Méndez et al. 2002, García-Gutiérrez et al. 2012), and different formulations and dosage of selective insecticides (Castillejos et al. 2002, Zamora et al. 2008, Rosas-García et al. 2009) are examples of some of the published research. Although "bio-rational" insecticides have been shown effective and are available in the domestic market, their current use in Mexico is negligible, in part due to relative cost. For example, retail price of a *Bacillus thuringiensis*-based insecticide is often twice as much as that of a synthetic insecticide; these products are only used in ≈1.5% of the maize crop area grown in Mexico (Tamez Guerra et al. 2001). This type of relevant IPM information, however, is mostly published in academic journals where it is not accessible to most growers.

Perhaps the greatest obstacle for full implementation of maize IPM programs in Mexico is the large number and great diversity of growers. Approximately 2 million growers plant maize under very diverse conditions across Mexico; 28% of the 1.8 million maize fields in Mexico are between 1 and 2 ha in area (SAGARPA 2013). This makes it a great challenge to deliver practical information and appropriate solutions. An IPM program represents a holistic approach that requires recognizing and quantifying biological control agents and pests, to have knowledge of pesticides, and to adopt better adapted plant varieties for specific regions. What proves even more difficult is coordinating all these concepts and actions with crop irrigation and tillage, planting schedules, fertilization and harvesting, and to have knowledge of the markets, among other practices (Morse and Buhler 1997). Solid IPM programs require continuing education because pest species, population dynamics, and action threshold, considered the "pillars" of IPM (U.S. EPA 2013), can vary significantly as new knowledge and technologies become available, as new pests emerge, and as climate and economic outlook changes. Morse and Buhler (1997) point out that perhaps an IPM program corresponds more to the characteristics of the researchers and academics that develop these programs, than to the actual needs of the grower, as the former tend to specialize in a given discipline, or even worse, in a specific part of the problem, leaving the remaining parts of the development and implementation of an IPM program to other colleagues (Morse and Buhler 1997). For growers to evaluate the impact of each of the IPM components and adopt them, they require highly specialized knowledge of diverse disciplines. This may be overwhelming and can lead to adoption of more user-friendly and quicker solution to the problem, which often implies the use of pesticides, without taking into account all the factors that may justify this practice. Growers can be persuaded initially to adopt an IPM program through a financial analysis and later on, regulatory and environmental considerations may dictate the extent to which programs are adopted (Koul and Cuperus 2007). A critical financial analysis is key for an IPM program, and the lack of interdisciplinary considerations in these analyses is generally not discussed (Lipke et al. 1987). It is not surprising that most of the information on IPM flows through the agrochemical suppliers and distributors (Koul and Cuperus 2007), which may explain why pest control consists mostly of pesticide use.

Most of the information on maize pests and IPM in Mexico has been published in technical bulletins of a reduced regional scope or in difficult-to-access reports, generally describing laboratory screenings, preliminary field evaluations, or listing technical recommendations, but rarely include products and practices that growers actually use. The goal of this report is to provide up-to-date information on the common pests in main maize-growing areas of Mexico from experts in the field. Updated information on maize pest population dynamics and control has been gathered from agricultural professionals directly involved in maize crop protection. This critical information, not readably available for Mexican production systems, is intended to help researchers, government officials, and industry specialists in making decisions regarding time and resource allocations, and in the design and implementation of IPM techniques, practices, and programs in Mexican maize.

Approach and Methods

Between 2010 and 2013 an expert panel composed of Mexican researchers and crop advisors gathered information regarding the main maize pests that reduce maize production and require control. Expert panels have been used successfully to gather base line data in the absence of formal documentation (Department of Environment and Primary Industries [DEPI] 2014). The geographical areas where information was obtained included commercial and self-consumption production systems and maize grain and silage production, information based on statistics obtained from the Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (Secretariat of agriculture, livestock, rural development, fisheries and food; SAGARPA 2013; Table 1).

Detailed information was gathered from agricultural specialists who provided data from commercial maize in different regions of Mexico. Responses to a common questionnaire were obtained from 24 participants including established researchers and technical personnel who were asked to—1) list the important arthropod pests that cause yield loss in the region; 2) identify the developmental stages of maize in which each pest species causes crop injury; 3) list the types of control strategies used for each pest or pest complex and its relative cost; and 4) discuss the kind of integrated crop and pest management tactics used (if any) and their elements.

Answers were received from experts representing seven growing regions: 1) "Bajío," which includes the states of Guanajuato, Michoacán, and Querétaro; 2) Chiapas state; 3) Chihuahua, where data were obtained from five different regions within the state; 4) "Laguna," including data from Coahuila and Durango states; 5) "Pacific," with information from Colima, Jalisco, and Nayarit states; 6) "Northwest," the southern portion of Sonora and the northern part of Sinaloa states; and 7) Tamaulipas state, north and south (Table 1). These seven regions represent almost half (45%) of the maize grain production area

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Table 1. Corn production in Mexico in 2011 in selected regions and nation-wide statistics

	Spring–summer planting				Autumn–winter planting			
	Irrigated		Rain fed		Irrigated		Rain fed	
	Hectares	Yield[a]	Hectares	Yield[a]	Hectares	Yield[a]	Hectares	Yield[a]
				Grain production				
Bajío	220,648	7.12	446,137	1.47	10,421	4.37	142	2
Chiapas	1,200	3.19	590,096	2.28	10,120	4.47	105,027	1.5
Chihuahua	97,925	8.6	20,546	0.45	0		0	
Laguna	30,205	3.98	64,361	0.37	49	3.5	0	
Northwest	10,913	4.77	32,217	0.9	392,518	6.66	3,622	2.5
Pacific	38,316	5.94	523,415	4.04	8,620	5.35	3,808	4
Tamaulipas	6,462	2.2	26,624	1.13	89,726	4.94	1,616	1.32
COUNTRY	668,183	5.91	4,392,199	2.11	578,677	6.41	430,033	1.67
				Silage production				
Bajío	16,506	55.92	50	11	134	22	0	
Chiapas	0		0		0		0	
Chihuahua	13,250	38.82	10,857	5.21	0		0	
Laguna	39,265	47.03	24,895	5.98	0		0	
Northwest	629	14.08	320	8.06	0		0	
Pacific	19,902	27.59	80,523	29.42	632	27.85	943	19.82
Tamaulipas	0		0		0		0	
COUNTRY	130,646	49.01	177,794	17.55	1356	32.16	1,430	26.06

Information source: http://siap.gob.mx/index.php?option=com_wrapper&view=wrapper&Itemid=351
[a] Thousands of kilograms per hectare.

Table 2. Presence of the fall armyworm, *S. frugiperda*, larvae in corn in different corn-growing regions of Mexico indicating the crop development stage

[a]		Dec.		Jan.		Feb.		Mar.		April		May		June		July		Aug.		Sep.	
1	Bajío												V2	V4	V6						
1	Chiapas															V2	V12	V2	V12		
1	Chih SE										V2	V4	V6	V8							
1	Chih NE											V2	V4	V6	V8						
1	Chih N												V2	V4	V6	V8					
2	Laguna							V2	V4	V6	V8					V2	V4	V6	V8		
1	Northwest	V2	V3	V4				V2	V4												
2	Pacific													V2	V4	V6					
1	Tamp N							V2	V4	V6	V8	V12									
1	Tamp S			V2	V4	V6	V12	R1									V2	V4	V10	VT	R2

Corn development stages according to http://weedsoft.unl.edu/documents/growthstagesmodule/corn/corn.htm.
[a] Pest problem ranking.

(2,734,734 hectares) and two thirds (67%) of the maize production in the country (Table 1).

Additional information on the use of insecticides on maize and growers' preferred products was obtained from a confidential pesticide market research study conducted in 2009, commissioned by an agrochemical company, which was used only as comparison for our data. Calculation of the environmental impact of pesticides (Kovach et al. 1992) was carried out through the Cornell University's web page (Cornell University 2014). Information of peer-reviewed papers on the subject published in accredited journals from 2000 to 2012 was obtained on the World Wide Web (Internet) through the Biosis search engine using the key words "pests" and "Mexico," including only those reports where the authors were affiliated with a Mexican institution.

Results and Discussion

S. frugiperda is the main pest of maize in five of the seven regions, nearly 3 million hectares in our survey region, representing 45% of all maize planted in Mexico (Table 1). In the other two regions (Laguna and Pacific), *S. frugiperda* was the second most important pest infesting all 2.9 million hectares represented in this survey (Table 2; Fig. 1). The fall armyworm is controlled with two to three applications of insecticide (Table 3). According to a survey carried out in Mexico by a marketing company in 2009 (Dow AgroSciences, personal communication), including maize farmers in all the regions of the country, growers agreed that the fall armyworm is the most difficult pest to control.

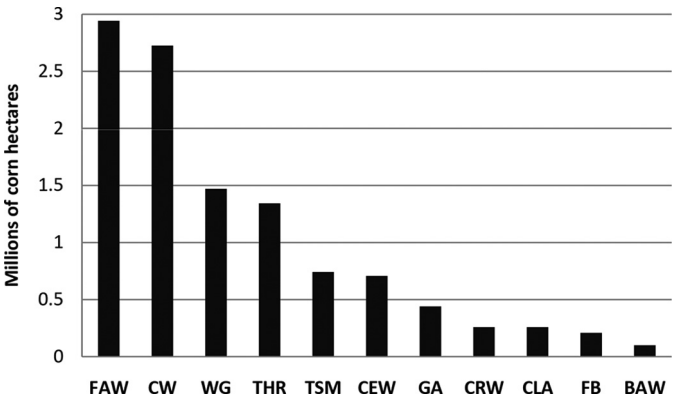

Fig. 1. Hectares affected by different maize pests in Mexico. FAW, *Spodoptera frugiperda*; CW, *Agrotis ipsilon*; WG, *Phyllophaga* spp., and other white grubs; THR, *Frankliniella* sp./*Thrips tabaci*; TSM, *Tetranichus urticae*; CEW, *Helicoverpa zea*; GA, *Sitobion avenae*; CRW, *Diabrotica* spp.; CLA, *Rhophalosiphum maidis*; FB, *Epitrix* sp.; BAW, *Spodoptera exigua*.

There are no good examples of comprehensive IPM programs for maize in any of the regions studied in Mexico. Although Mexican

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Table 3. Insecticides used to control different corn pest in Mexico

	Rate (g AI/ha)	EIQ[a]	Bajío (2)	Chiapas (2)	Chih SE (2)	Chih NE (2.5)	Chih N (2)	Laguna (2)	Pacific (2)	Northwest (2)	Tamp N (2)	Tamp S (2)
Abamectin	11.1	0.3			BGM (2.5) TSM (1.5)		TSM (1)	BGM (2.5) TSM (1.5)		TSM (1)		
Acephate	1,088	24.9					FAW (2), CEW (1.5)					
B. thuringiensis[b]	52[b]	7.2					BAW (<0.5)		FAW (2)			
Carbofuran	1,000	45.2	WG (1–1.5)		CW (1)		WG (<0.5)	CW (1)	WG (2)			
Chlorfenapyr	120	1.6					CEW (1.5)					
Chlorpyriphos	480	11	FAW (2), WG (1.5), *Nte* (2), LMB (2)	FAW (2), CW (1)	FAW (2), CW (1)	CEW (2.5), BAW (1)	FAW (2), CEW (1)	FAW (2), CW (1)	FAW (2), WG (2), BAW (1)	FAW (2), CEW (1), CW (1)		FAW (2)
Diazinon	1,000	39.3					WG (<0.5)					
Diflubenzuron	48	1.0					BAW (<0.5)					
Dicofol	368–613	9.4			BGM (1) TSM (1.5)		TSM (0.5–1)			TSM (1)		
Dimethoate	435	12.5	THR (1)		FB (1.5), CRW (1.5), THR (1), CLA (1)			FB (1.5), CRW (1.5), THR (1), CLA (1)				
Emamectin benzoate	10–16	2.2	FAW (2)			FAW (2.5)	FAW (2), CEW (1.5)			FAW (2), CEW (1)		FAW (2)
Fenpyroximate	75	1.2			BGM (2.5) TSM (1.5)			BGM (2.5) TSM (1.5)				
Methamidophos	841	26.5			FB (1.5), CRW (1.5), THR (1)	CLA (1)	FAW (2), CEW (1)	FB (1.5), CRW (1.5), THR (1)		GA (1)		
Methomyl	450–508	8.5		FAW (2), CW (1)	FAW (2), FB (1.5), CRW (1.5), THR (1), CLA (1)	CEW (2.5), BAW (1)		FAW (2), FB (1.5), CRW (1.5), THR (1), CLA (1)		FAW (2), CEW (1), CW (1)		
Methyl parathion	720	13.1	*Nte* (2), LMB (2)									
Novaluron	44–88	0.5					FAW (2)		FAW (2)			
Omethoate	400	11.5					TSM (<0.5)					
Phorate	1,125	49							WG (2)			
Propargite	1,178–2,731	106					TSM (0.5)					
Pyrethroids[b]	35–188	1.1	FAW (2), *Nte* (2), LMB (2)	FAW (2), CW (1)	FAW (2)	CEW (2.5), BAW (1)	FAW (2), CEW (1.5), TSM (0.5)	FAW (2)	FAW (2), BAW (1)	FAW (2), CW (1)	FAW (2), CEW (1)	FAW (2), CEW (1)
Rynaxypyr	50	NA										FAW (2)
Spinetoram	Jun-50	1.2	FAW (2)	FAW (2)	FAW (1)		BAW (<0.5)			FAW (2), CEW (1)		FAW (2)
Spinosad	35	0.4				FAW (2.5)						
Spiromesifen	120	2.9			BGM (2.5) TSM (1.5)			BGM (2.5) TSM (1.5)				
Terbufos	1,000	58.9	WG (1–1.5)						WG (2)			
Thiodicarb	235	4.7			CW (1)			CW (1)				

The number in parenthesis refer to the average number of applications per pest in a particular region.

BAW, *S. exigua*; CEW, *H. zea*; CRW, *D. virgifera*; CW, *A. ipsilon*; FAW, *S. frugiperda*; FB, flea beetle (*Epitrix* sp.); GA, *Sitobion avenae*; LMB, *Nicentrites testaceipes*; THR, Thrips; BGM, *Oligonychus pratensis*; TSM, *T. urticae*; WG, *Phyllophaga* and other white grubs; CLA, *Rhophalosiphum maidis* and *Sitobion avenae*.

[a] Environmental impact (EIQ) calculated for one application at its lowest recommended rate from: http://cceeiq-lamp.cit.cornell.edu/EIQCalc/input.php?cat.

[b] Calculated for Dipel 54% and expressed as *B. thuringiensis* fermentation solids, spores, and insecticidal toxins.

[c] Calculated for alpha cypermethrin, the most commonly used pyrethroid.

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scientists have contributed with partial information to implement IPM programs, we found that very few crop advisors or growers have heard of a maize IPM or similar programs. Although maize is the most important crop in Mexico, we are not aware of IPM programs for Mexican maize production. Even when some IPM elements have been identified in some places (e.g., the role of beneficial organisms in northern Tamaulipas), and have been developed for specific Mexican conditions, they are not being used as a valuable and consistent tool.

Numerous studies have identified scores of microbes and animals that can control pests of maize in Mexico, particularly *S. frugiperda* (Molina-Ochoa et al. 2001, Cortez-Mondaca et al. 2012, Estrada-Virgen et al. 2013), which in ≤10% of the cases can reduce populations of this pest below action threshold (Molina-Ochoa et al. 2004), which is ≥20% of the plants with *S. frugiperda* larvae (Cruz and Turpin 1983, Harrison 1984, Fernández 2002). However, this information is mostly found in scientific papers to which most growers have no access. For the same reason, other effective control alternatives, such as the use of beneficial nematodes (Molina-Ochoa et al. 1999), biological control along with bio-rational insecticides (Méndez et al. 2002), timely use of insecticides that have a lower impact on beneficial fauna (García-Gutiérrez et al. 2012), and different formulations and dosage of selective insecticides (Castillejos et al. 2002, Zamora et al. 2008, Rosas-García et al. 2009), are also little known components of IPM programs that are not widely implemented. With all this valuable information available, most growers are still faced with lack of basic knowledge regarding identification and impact of natural enemies, in addition to the difficulty of finding bio-rational insecticides, which usually cost approximately twice as much as pyrethroids and organophosphates (Tamez Guerra et al. 2001, Castillejos et al. 2002).

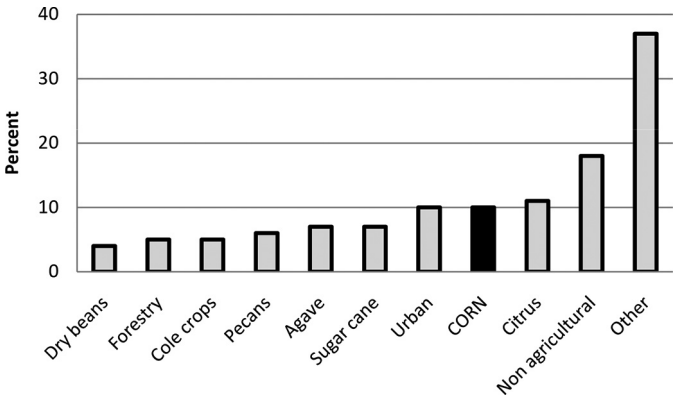

Fig. 2. Percent of peer-reviewed reports of different arthropod pests of Mexican crops between 2000 and 2012.

The need for developing more efficient and environmentally sustainable pest control strategies in Mexican maize production may be reflected in the quantity of entomological research published by Mexican scientists in the past decade. Figure 2 illustrates that the number of reports in peer-reviewed journals of research conducted with different pests of Mexican crops during a 12-yr period has had a disproportionate bias toward crops other than maize, which does not reflect the importance of a crop that represents nearly 7 million hectares and 30% of the domestic agricultural output. For example, citrus pests have been the subject of as many publications as maize pests, in spite of the great difference of the planted area (only 13% for citrus compared with 30% for maize). The same is true for the reports of arthropod pests of sugarcane, agave, and cruciferous crops, with planted areas that are only 9.9, 1.8, and 2.9% of the maize area, respectively. Maize has been the subject of only 10% of these scientific reports in the past decade.

Based on the responses by the expert panel, the main criteria in selecting an insecticide to control pests of maize are the effectiveness and speed of action, the residual effect, the price, and the power of a particular insecticide to control more than one pest species. For example, methamidophos, which is a relatively inexpensive product (≈US$10.00 per hectare) and used by 5% of Mexican maize growers, can be sprayed against Lepidoptera and thrips in different occasions in the same crop cycle as the need arises (Table 3), and in regions where these pests appear simultaneously in maize, such as in Bajío (Tables 2, 4, and 5). Alternatively, the use of methomyl (US$5.60 per hectare) in Laguna and part of Chihuahua (Table 3) offers a clear advantage to all growers, as they can control several problems with one product, and methomyl can be used on different crops to control a wider spectrum of pests. Selectivity on beneficial organisms was not mentioned as criteria by any of the survey respondents, neither bio-rational insecticides which are typically more specific and costly alternatives, or any other IPM tool.

Access to and technical support of conventional pesticides may also favor their continued use over alternatives. Agrochemical production and distribution networks are in place to service even the small farm; more than half of maize farms in Mexico are <2 hectares (SAGARPA 2013). Commercial formulations of common broad-spectrum pesticides are readily available in small containers (1 liter) even in remote areas. These pesticides generally act with greater efficacy and speed on contact or ingestion than biological insecticides that typically must be ingested by the insect pest. Five of the 11 insecticides generally used against *S. frugiperda* (Table 3) act on contact and ingestion: spinetoram, emamectin benzoate, pyrethroids, methomyl, and chlorpyrifos; the last three being less expensive, but also highly toxic against beneficial arthropods (Armenta et al. 2003, Thompson 2013). Additionally, the agrochemical distribution network has a greater presence throughout the country than agricultural education

Table 4. Presence of other Lepidoptera larvae in corn in different corn-growing regions of Mexico indicating the crop developmental stage

[a]		Jan.	Feb.	Mar.		April		May		June		July		Aug.		Sept.		Oct.		Nov.	
								Black cutworm, *Agrotis ipsilon*													
4	Bajío							VE	V2	V4											
2	Chiapas									VE	V2	VE	V2								
5	Chih SE					VE	V2														
4	Laguna				VE	V2						VE	V2								
2	Northwest		VE	V2	V2															VE	V2
4	Pacific									VE	V2	V4									
								Beet armyworm, *Spodoptera exigua*													
3	Chih NE							V2	V4	V6	V8										
4	Chih N								V2	V4	V6	V8									
								Mexican rice borer, *Eoreuma loftini*													
2	Tamp S	V3	V6	V12	R2									V4	V8	VT	R3	R5			

Corn development stages according to http://weedsoft.unl.edu/documents/growthstagesmodule/corn/corn.htm.
[a] Pest problem ranking.

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Table 5. Presence of coleopteran pests in corn in different corn-growing regions of Mexico indicating the crop developmental stage

[a]		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.
						Phyllophaga spp. and other white grubs						
2	Bajío					VE V2 V4						
9	Chih SE					V2 V2 V4						
6	Chih N					V2 V2 V4						
1	Pacific					S VE V2 V4						
						Corn rootworms, *Diabrotica* spp.						
6	Chih SE					V8 V12 VT R1				V8 V12		
5	Chih N					V8 V12 VT R1						
6	Laguna				V8 V12 VT R1				V8 V12 VT R1			
						Flea beetles, *Epitrix* sp./*Chaetocnema* sp.						
3	Chih SE					V8 V12 VT R1						
3	Laguna				V8 V12 VT R1				V8 V12 VT R1			
						Lesser maize billbug, *Nicentrites testaceipes* (Champion)						
3	Bajío					VT R1						

Corn development stages according to http://weedsoft.unl.edu/documents/growthstagesmodule/corn/corn.htm.
[a] Pest problem ranking.

networks that may provide information on alternatives to broad-spectrum pesticides, which can greatly influence decision making in pest management (Koul and Cuperus 2007).

In addition to fall armyworm, other important pests of Mexican maize include mites *Oligonychus pratensis* (Banks) and *Tetranychus urticae* Koch primarily damaging silage maize in Laguna and parts of Chihuahua (Table 6) and affecting almost 1.5 million hectares of the area of our survey (Fig. 1), and the *Phyllophaga* spp. white grub complex in the Pacific and Bajío regions (Table 5), with similar geographic impact (Fig. 1). Other Lepidoptera pests are also very important in Mexico. The black cutworm, *Agrotis ipsilon* (Hufnagel), is controlled with insecticides on 2.2 million hectares (Fig. 1). However, this insect is relatively easy to manage (one insecticide application, Table 3); therefore, respondents to our survey ranked it as second to fifth in importance (Table 4). *Helicoverpa zea* (Boddie) is considered a serious problem in four of the seven regions (Table 7), impacting 700,000 hectares (23%), requiring between one and three sprays per crop cycle (Table 3). The beet armyworm, *Spodoptera exigua* (Hübner), and the Mexican rice borer, *E. loftini*, were considered among the five most harmful pests (Table 4). Although *S. exigua* only affects 100,000 ha of our survey area (Fig. 1), it requires one to three insecticide applications (Table 3).

Host plant resistance has been used to reduce the impact of Lepidoptera pests, mainly *S. frugiperda* in Mexico. Zapalote Chico and Antigua varieties have shown to be resistant to fall armyworm, corn earworm, and other Lepidoptera pests that attack different parts of the plant (Williams et al. 1978, Wiseman and Davis 1990, Abel et al. 2000). Maize host plant resistance efforts often rely on recombinant DNA techniques to develop genetically modified (GM) hybrids (mainly expressing proteins of *Bacillus thuringiensis*) and ribonucleic acid interference (RNAi), effective strategies against Lepidoptera and Coleoptera pests (Lynch et al. 1999, Nuessly et al. 2007, Price and Gatehouse 2008). Pest-resistant maize derived from crosses with Zapalote Chico or Antigua is not very common in commercial hybrids currently available, likely due to emphasis on development of GM varieties (W. P. Williams, 2013, personal communication). A clear advantage of recombinant DNA technologies that produce GM varieties over traditional ones was determined by comparing the performance of a GM *B. thuringiensis*-expressing variety with a conventional maize variety to which pyrethroids were applied eight times (>200 g ai/ha) to protect from a heavy infestations of *S. frugiperda* and *H. zea*. The GM hybrid with no synthetic insecticide applications produced 100% ears free from insect damage, whereas the conventional hybrid treated multiple times with insecticide produced only

Table 6. Presence of several pests in corn in different corn-growing regions of Mexico indicating the crop developmental stage

[a]		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.
						Banks grass mite, *Oligonychus pratensis*/two-spotted spider mite, *Tetranychus urticae*					
2	Chih SE						V8 V12 VT R1				
4	Chih NE						V8 V12 VT R1				
3	Chih N							V8 V10 V12 VT R1			
1[b]	Laguna					V8 V12 VT R1		V8[b] V12 VT R1[b]			
6	Northwest				V4 R1						
						Corn leaf aphid, *Rhophalosiphum maidis* Fitch					
7	Chih SE						V8 V12 VT R1				
5	Chih NE						V8 V12 VT R1				
7	Laguna					V8 V12 VT R1				V8 V12 VT R1	
						Grain aphid, *Sitobion avenae*					
4	Chiapas									R1 R1	
4	Northwest	R1	R1		R1 R1						
						Thrips, *Frankliniella* sp./*Thrips tabaci*					
4	Bajío					VE V2					
4	Chih SE						V8 V12 VT R1				
4	Laguna					V8 V12 VT R1				V8 V12 VT R1	
4	Northwest			VE V2							
						Corn leafhopper, *Dalbulus maidis* (De Long & Wolcott)					
5	Chih N								VT R1		

Corn development stages according to http://weedsoft.unl.edu/documents/growthstagesmodule/corn/corn.htm.
[a] Pest problem ranking.
[b] In the summer corn planting this pest is ranked number 8.

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Table 7. Presence of the corn earworm, *Helicoverpa zea*, larvae in corn in different corn-growing regions of Mexico indicating the crop developmental stage

[a]		Jan.	Feb.		Mar.		April	May	June	July		Aug.		Sept.		Oct.
3	Chiapas									V8	V12	V8	V12			
8	Chih SE										R1					
2	Chih NE									VT	R1					
2	Chih N												VT	R1		
7	Laguna								R1							R1
3	Pacific	R1	R1		V2	V4										
2	Tamp N						V8	V12								
3	Tamp S			V12	R1									R1	R2	

Corn development stages according to http://weedsoft.unl.edu/documents/growthstagesmodule/corn/corn.htm.
[a] Pest problem ranking.

18% of ears with no fall armyworms and corn earworms (Shelton 2012). In another study comparing GM and conventional maize varieties, a 71% yield loss due to *S. frugiperda* attack was documented only in the conventional variety (Buntin et al. 2001). This level of performance has lead to broad adoption of GM maize hybrids in different countries.

Data generated in Mexico have yielded similar results. GM maize compared with insecticide-treated (two to five applications ranging between 720–3,600 g ai/ha) conventional maize, showed 10% higher yields and effective control of fall armyworm and corn earworm infestations (Piña and Solleiro 2013). Reducing injury by *S. frugiperda* and *H. zea* to maize ears may also lead to reductions in the levels of aflatoxin (known carcinogen) produced by the fungus *Aspergillus flavus* (Gourama and Bullerman 1995, Boermans and Leung 2007, Williams et al. 2010).

However, the availability of improved hybrids developed through conventional or recombinant DNA technologies for small growers in Mexico faces great obstacles. Most of the small growers likely cannot afford the extra cost of insect-resistant hybrid seeds. Hybrid seed prices (≈US$250.00/ha) represents almost half of the expected income from grain sales that a typical Mexican producer may obtain (not factoring government subsidies). The promising side of this situation is that seed companies have realized that even small growers are interested in improved varieties and in some areas of Mexico, maize hybrids are offered in small quantities (60,000 seeds per sack) to plant as little as one hectare. This indicates there is a viable market for improved maize seed for the small growers in Mexico. Interestingly, two or three insecticide applications per crop (Table 3) at a cost of US$30–45/ha may be sufficient to keep the pest complex in check (not only Lepidoptera pests) in most instances. This is far below the cost of hybrid seed and may be particularly advantageous to the small farmer facing a diverse pest complex. Thrips, aphids, and mites were reported as important pests in almost half of the regions represented in our survey (Table 6) and cannot be effectively controlled by GM maize hybrids at this time. The future development of elite hybrids providing some type of cross-resistance and a significant increase in maize yields would drastically change the above equation.

Wide implementation of IPM of insects in Mexican maize is not a lost cause, but further delays in finding solutions to the low productivity challenge, which is partly a consequence of inadequate pest management, may force the country to continue importing ≈30% of its maize grain to keep up with internal demand (SAGARPA 2013). Lack of adoption of IPM tactics will likely lead Mexican maize growers to continue applying conventional pesticides to combat major pests (≈3,000 tons of active ingredient per year for a single pest; Blanco et al. 2010).

Possible solutions to these problems may be achieved by "1) a change in pest management approaches through demonstration-research plots where growers can verify the benefits of IPM programs," along with public campaigns. Similar programs have been successful for other crops in Asia where marked reductions in insecticide use and higher crop yields have been documented (Normile 2013); "2) an easy and accessible way for growers to recognize and understand the function of natural enemies and the benefits of bio-rational alternatives in minimizing negative impact of pesticides on beneficial organisms." As the use of the Internet becomes more common, information dissemination becomes easier. There are different sites available on the World Wide Web containing relevant information, but a better portal should be created to link the work of Mexican professionals directed at solving specific pest problems; "3) development and marketing of pest-resistant maize hybrids through effective and affordable methods to reduce the need for broad-spectrum pesticides." This should include a science-based assessment on the impact of agricultural biotechnology taking advantage of the great maize genetic diversity present in Mexico to identify appropriate sources of host plant resistance; "4) development and marketing of bio-rational products and biological control products for the small farm" (smaller, lower cost packaging). This should also involve greater knowledge dissemination of the ecology of crops and herbivores for better managing the latter; and "5) other elements" including training of involved technical personnel on technology transfer and spreading of information, on government policies reflecting present day production of maize and on assessment and ongoing evaluation of programs (Council for Agricultural Science and Technology [CAST] 2003).

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