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Issues

Agronomic and Environmental Impacts of Bt Cotton in Mexico

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*This report is dedicated to the memory of our friend and colleague Antonio 'Pale' Terán-Vargas.

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Abstract

Worldwide cotton production was characterized by the highest pesticide input among the row crops. Mexico was not the exception, because at some point, cotton fields were sprayed with insecticides up to 18 times in a single crop season, most of them targeted to lepidopteran pests, and even with that intensive application regime, growers lost 30–50% of the potential yield, increased their production costs by 35%, mainly due to pests highly resistant to insecticides. With the availability of *Bacillus thuringiensis*' Berliner (Bacillales: Bacillaceae) protein-expressing cotton (Bt cotton) in Mexico more than 20 yr ago, cotton's pest management in the country has changed substantially. Growers use significantly less insecticide (50% less), and they are not worried about *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) (pink bollworm) and *Chloridea virescens* (Fabricius) (Lepidoptera: Noctuidae) (tobacco budworm), pests that were extremely important at some point due to their negative impact on yields. The *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) (bollworm) populations, another limiting pest, are also no longer of concern, except in one small region of Mexico. *Anthonomus grandis* Boheman (Coleoptera: Curculionidae) (boll weevil), another very important pest, is not controlled by current Bt cotton cultivars, and binational eradication programs have been implemented in different regions of Mexico and the United States. In areas where *A. grandis* has not been eradicated but are currently within the eradication program, insecticide use has increased, because the goal is to disrupt the biological cycle of the pest using different techniques. Once the boll weevil eradication is achieved, it is expected that the use of insecticide will diminish, as has been the case in other now *A. grandis*-free areas. Currently, sucking insects such as *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), *Nezara viridula* (Linnaeus) (Hemiptera: Pentatomidae), *Lygus* spp. Hahn (Hemiptera: Miridae), and *Chlorochroa ligata* (Hemiptera) (Say) (Hemiptera: Pentatomidae), for which current Bt cotton cultivars have no effect, are the 'new' pest problems of cotton production. Mexico is a unique example of the management of cotton pests. In order to continue as the world leader in cotton production per area, eradication programs for *A. grandis* and *P. gossypiella* have been successfully established, the latter supported by the high adoption of Bt cotton. These strategies that are part of an integrated pest management program have allowed insecticide use to be reduced by half, preserved the susceptibility to *B. thuringiensis* for more than two decades, and have continued to increase cotton yields for more than 20 yr.

Resumen

La producción mundial de algodón requería de un número elevado de aplicaciones de insecticidas, por eso se consideraba que el algodonero era el que más contaminaba de los cultivos en surco. México no era la excepción, ya que en ciertas épocas solían hacerse hasta 18 aplicaciones de insecticidas las cuales llegaron a ser inefectivas contra insectos plagas que ya habían desarrollado resistencia a éstos, causando pérdidas elevadas de rendimiento

(30–50%) e incrementos en los costos de producción (alrededor del 35%). Con la disponibilidad de algodonero Bt desde hace dos décadas, el manejo de plagas ha cambiado radicalmente, ya que le ha permitido al agricultor dejar de aplicar esas cantidades de insecticidas –y de preocuparse- contra *Pectinophora gossypiella* (gusano rosado) y *Chloridea virescens* (gusano tabacalero), plagas que fueron devastadoras en algún momento. Las poblaciones de *Helicoverpa zea* (gusano bellotero), usualmente altas y perjudiciales, continúan siendo de consideración solo en una región. Otra plaga de bastante importancia, *Anthonomus grandis* (picudo del algodonero), que no es controlada por las variedades actuales de algodonero Bt, continua limitando la producción en algunas zonas de México, donde el programa binacional para su erradicación no se ha concluido/implementado. Durante este programa se han necesitado cantidades elevadas de insecticida para romper el ciclo biológico de *A. grandis* y obtener su erradicación, pero una vez logrado este objetivo, se espera una mayor reducción en el uso de insecticida en algodonero, tal como ha ocurrido en las regiones declaradas zonas libres de esta plaga. Actualmente, los insectos chupadores *Bemisia tabaci*, *Nezara viridula*, *Lygus* spp., y *Chlorochroa ligata* (Hemiptera) constituyen 'nuevos' problemas de manejo de plagas, para los cuales los cultivares de algodonero Bt no tienen efecto. México representa un ejemplo único en el manejo actual de las plagas de este cultivo, ya que sigue siendo uno de los países con más alto rendimiento de algodón, para lo cual se han establecido programas exitosos de erradicación de *P. gossypiella* y *A. grandis*, basados en su manejo integrado y una fuerte adopción de algodonero Bt desde hace dos décadas, lo que ha permitido reducir el uso de insecticidas a la mitad, preservar la susceptibilidad de plagas objetivo a las toxinas del *Bacillus thuringiensis,* e incrementar sustancialmente el rendimiento de algodón por más de 20 años.

Key words: Bt cotton, pest incidence, insecticide use, EIQ value, Mexico

Mexico is one of the major cotton-producing countries in the world (Beckert 2014, USDA-FAS 2018). However, its cultivation has had negative impacts on the environment and in some rural communities (García *et al.* 1988). Intensive cotton production is a large economic investment, and in order to maximize yields and returns, growers provide their plants with the best suitable conditions, including intensive management of pest insects. This is one of the reasons why cotton has been considered one of the row crops with the highest input of pesticides (Deguine *et al.* 2008). Notably, Mexico has been portrayed as an example of the undesired consequences of inadequate agronomic practices that have given rise to unmanageable insecticide resistance, forcing growers to spray up to 18 times without being able to achieve satisfactory control (Metcalf and Luckmann 1994, Terán-Vargas *et al.* 2005). For the past two decades, with the introduction of genetically engineered cotton that expresses *Bacillus thuringiensis* toxins (Bt cotton), Mexico still maintains the highest cotton production per area of the world, and has reduced the use of insecticides by more than half, while preserving the susceptibility to *B. thuringiensis* proteins in targeted pests. These outstanding achievements are the outcome of a positive and constant interaction between growers, researchers, industry and regulatory agencies.

The production regions where Mexico's cotton is cultivated vary greatly; from semi-tropical to arid climates. All these regions experience intense pest pressure. Pink bollworm (*Pectinophora gossypiella*), bollworm (*Helicoverpa zea*), tobacco budworm (*Chloridea virescens*) (Lepidoptera), and the boll weevil (*Anthonomus grandis*) (Coleoptera), have been devastating pests at some point in time, especially before the use of Bt cotton. Before the use of Bt traits/technology in Mexico, growers applied as many as 18 insecticide applications targeting primarily lepidopteran pests, such as *P. gossypiella, H. zea,* and *H. virescens* (Terán-Vargas *et al.* 2005). Nearly complete control of these pests using Bt cotton has shifted the insect pest spectrum and reduced the number of insecticide applications in the most important cotton-growing regions of Mexico (Table 1). Currently, sucking insects such as *Bemisia tabaci, Lygus* spp., and *Chlorochroa ligata* (Hemiptera), are the main pest problems of cotton production.

In this work, we analyze the impacts of the deployment of Bt cotton on insecticide reduction, pest populations, and cotton yields in Mexico.

Methods and Approach

We gathered information on pest densities, type and amount of insecticides applied, cotton field yields, and performed tests to evaluate the susceptibility of targeted pests to *B. thuringiensis* proteins. The data were obtained from proceedings of the Binational International Committee on cotton, from the Binational Pink Bollworm and Boll Weevil eradication programs, Mexican states' committees of plant health (Comités Estatales de Sanidad Vegetal), SAGARPA-SIAP website, peer-reviewed articles, Mexican universities' information, 2015–2016 cotton growers surveys (Rocha-Munive *et al.* 2018), and the professional opinion and experience of the authors of this report. Additionally, in the 'La Laguna' region (Durango and Coahuila States) in 2016, four commercial non-Bt and four Bt fields were evaluated to determine the pest complex and levels of infestation and damage. Using the insecticide use data in commercial cotton fields during 1982–1989, and in 2016 in La Laguna, the environmental impact quotient (EIQ, Kovach et al. 1992) was calculated.

Results and Discussion

Impacts of Bt Cotton on Insecticide Use and the Environment

The data in Table 1 indicate that not all the cotton areas of Mexico have been under an intensive insecticide spray regime. However, throughout the country, the number of applications against lepidopterans has been reduced in all the regions, except for *H. zea* in southern Tamaulipas. Total number of applications may have increased in other areas, such as northern Tamaulipas and La Laguna, because growers make multiple applications against *A. grandis*, as a requirement of a binational program to eradicate this pest between Mexico and the United States (National Cotton Council of America 2018).

Spraying insecticides has been a serious consideration for the Mexican cotton grower. An average of ~9 insecticide applications targeting the whole pest complex was necessary before the use Bt cotton, representing 35% of the total production costs, and even with this investment in insecticide, growers still lost 30–50% of their potential yield due to pest attacks (CESAVECH 2015). A decade after the introduction of GE cotton cultivars, the average number of application dropped to 4 or less. In 2017, each application cost approximately $20.00/ha for the product and another $16.00/ha for the ground or aerial applications. In the same year, the average cost of cotton production in Mexico was calculated as $2,160 per hectare. If an average Mexican cotton grower produced 1,585 kg of cotton/ ha (USDA-FAS 2018), and the international cotton prices fluctuated around $1.86/kg that year (Index Mundi 2018), this shows that there was little margin of profit, especially for many Mexican farmers producing cotton on less than 5 hectares, for whom crop protection represents nowadays 11–12% of their investment. Therefore, 2–9 insecticide applications per crop season, due to the presence or eradication of pests not targeted by Bt cotton, can greatly reduce profits. In La Laguna, a highly productive area, cotton production averages 1,700–2,000 kg/ha, losing 5–20% of their potential yield due to *A. grandis* attack, while *Bemisia* spp., produced another 10% yield loss in 2017, and a harsh fiber quality production penalty ($50 per a 220-kg cotton bale) due to the presence of honeydew produced by this pest, affecting the color and industrialization of cotton fiber. None of the currently commercialized Bt cotton cultivars control non-lepidopteran pests such as those mentioned above. Mexican cotton growers who planted Bt cotton cultivars experienced 15% yield increase, saved between $9 and $120 in insecticide use, and obtained $267 more per hectare in the year 2015 (Brookes and Barfoot 2017).

A factor that has temporally increased the use of insecticides is another binational eradication program for pink bollworm in several cotton-growing regions. The first region under this coordinated effort was Chihuahua, where an increase in the number of insecticide applications began in 2001, and 3 yr after the *P. gossypiella* population plummeted almost entirely (Henneberry 2007), reducing the insecticide inputs afterward. In La Laguna, a documented 25-year trend of insecticide use on cotton fields serves as a detailed illustration for these trends (Fig. 1). Even though the data shows reductions in the number of insecticide applications in some regions and increase in others (Table 1), two factors need to be considered to fully understand this information: 1) during nearly two decades,

Table 1. Average number of insecticide applications per crop season at the time Bt cotton was first planted in Mexico (~1996) and for the past 4 yr (2014–2017)

Pest[a]	Baja California		Chihuahua		La Laguna[b]		Sinaloa		Sonora		Tamaulipas South		Tamaulipas North[b]	
	1996	≤2017	1996	≤2017	1996	≤2017	1996	≤2017	1996	≤2017	1996	≤2017	1996	≤2017
PBW	2	0	1.5	0	5.5	0	1	0	0	0	0	0	0	0
CEW	1	0	1.5	0	1.5	0	1	0	1	0	1.5	1.5	2	0
TBW	0	0	1.5	0	1.5	0	1	0	1	0	2.5	0	3	0
BAW	0	0	1	0	1.5	0	0	0	0	0	1	0	0	0
BW	0	0	4.5	0	0	≤9	3	3	3	3	≤20	≤4	≤3	8
WF	1	1	1	1	1	1.5	1	2	0	1	0	1	1	0
CB	0	0	0	0	1	1.5	0	0	0	0	0	0	0	1
HEM	1	1	1	1	0	0	1	1	1	1	0	0	0	0
Total	4	2	9	2	9	9[b]	7	4	5	4	22	6	7	9[b]

Data obtained from the Mexican Government and cotton growers' surveys. Details explained in Rocha-Munive *et al.* 2018.

[a] PBW, *Pectinophora gossypiella*; CEW, *Helicoverpa zea*; TBW, *Chlorídea virescens*; BAW, *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae); BW, *Anthonomus grandis*; WF, *Bemisia* spp.; CB, *Chlorochroa ligata*; HEM, Hemiptera complex (*Lygus* spp., *Nezara viridula*).

[b] Areas with active PBW and BW eradication program.

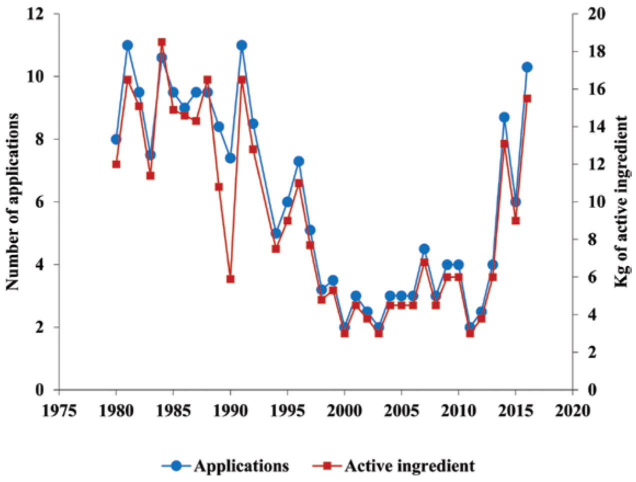

Fig. 1. Number of insecticide applications and amount of insecticide applied per cotton season in La Laguna, Mexico before Bt cotton was utilized (1997) and when the pink bollworm (*Pectinophora gossypiella*) and boll weevil (*Anthonomus grandis*) binational (Mexico-United States) eradication program was implemented (2014).

between the time when the use of Bt cotton became available (1996), and the latest growers' survey of the current number of insecticide sprays (2017), many factors were observed in cotton fields such as the fluctuation of Lepidoptera densities and nontarget pests such as hemipterans. The current pest spectrum of primarily 'sucking' insects, include *Lygus* spp. and *Nezara viridula*, while *Bemisia* spp., and *C. ligata*, once considered secondary pests, are now of primary concern in some regions of the country. 2) The increment in insecticide applications in La Laguna and Northern Tamaulipas regions are primarily due to the binational (Mexico–United States) eradication program for *A. grandis*.

There was a reduction in insecticide use in La Laguna, and throughout all the Mexican cotton areas after Bt cotton was introduced. With the availability of Bt cultivars (Table 2), the number of insecticide sprays was reduced by almost half until 2013, when the binational programs to eradicate pink bollworm and boll weevil were implemented. These programs do not take into consideration established action thresholds to protect the crop, but aim to break the reproductive cycle of the pests; therefore, to achieve this goal the use of insecticide has increased. The strategies of these temporary and successful programs include: the management of the crop to negatively affect the synchrony between the emergence of the moths and the presence of cotton plants in the field; mating disruption using pheromone lures; the release of millions of sterile pink bollworm moths to overcome the mating success of feral males; an aggressive control of larvae with synthetic insecticides; and a high percent of Bt cotton planting (Naranjo and Ellsworth 2010). The destruction of plants at the end of the season; trapping adults in pheromone traps; an aggressive control with insecticides, primarily ultra-low-volume rates of malathion (USDA-APHIS 2013), are the basis of another successful eradication program against the *A. grandis*. Table 2 shows that for the past 7 yr, Bt cotton planting has reached close to 96%, the maximum planting of Bt cotton recommended by the Mexican regulatory authorities as a strategy to delay the development of Bt-resistance. In areas where the pink bollworm eradication program has been established, the Bt cultivars have reached nearly 100%, surpassing temporarily the regulatory requirement of insecticide resistance management for Bt crops (E.P.A. 2007). In Mexico, regulatory requirement for refuge deployment consists of 80% Bt cotton and 20% conventional, in which the conventional may be sprayed with insecticides for lepidopteran control; or 96% Bt cotton and 4% conventional, in which the refuge may not be sprayed for lepidopteran control (Sotero Aguilar-Medel et al. 2017). The specific reduction of the environmental impact of cotton cultivation in Mexico is another success story. Before the availability of Bt cotton in La Laguna, growers used to spray 20 different insecticidal active ingredients on this crop, amounting to an average of 0.53 kilograms of active ingredient for each of the 9–18 insecticide application per crop season. The effect on the environment and the grower from such intense spraying amounted to ~19 EIQ units, values that take into consideration the physiological and toxicological characteristics of the pesticide, the chronic and dermal exposure, half-life of the active ingredient on the plant foliage and soil, the absorption probability by plants and animals, its persistence, and toxicity in fish, birds, bees and beneficial arthropods (Kovach *et al.* 1992). Before the implementation of the binational programs against *P. gossypiella* and *A. grandis*, cotton growers in La Laguna managed their pest complex with only six insecticidal active ingredients, averaging a total of 0.18 kg ai/ha for the ~5 total applications per crop season (Fig. 1), with an EIQ of 2.5 (Table 3). Currently, close to nine applications of malathion against *A. grandis* in La Laguna and northern Tamaulipas (Table 1), areas under its eradication program, has increased the amount of insecticide active ingredient and the EIQ in these regions up to 0.308 kg ai/ha and 23.92 EIQ (Table 3). Once the eradication program against this pest is declared completed, it is expected to lower the insecticidal input in this crop.

Impacts of Bt Cotton on Pest Populations and Resistance to Insecticide and Cry Proteins

The effectiveness of Bt cotton against *P. gossypiella* has been documented for nearly two decades in the United States (Carrière *et al.* 2003, Henneberry 2007). A similar situation has been observed in Mexico in the regions where this pest used to be one of the main problems. In La Laguna, before they had access to Bt cotton, half

Table 2. Percent adoption of Bt cotton in the most important cotton-producing areas of Mexico

Year	Baja California	Chihuahua	La Laguna	Sonora South	Sonora North	Tamaulipas South	Tamaulipas North
1996	0	0	0			31	0
1997	0	0	18			77	0
1998	2	2	46			88	0
1999	4	0	84			45	0
2000	7	0	78			42	0
2001	13	0	79			85	0
2002	10	57	80	71	23		0
2003	19	60	83	66	22		0
2004	24	68	80	77	37		0
2005	30	59	80	80	33		0
2006	26	51	80	24	63		0
2007	62	39	80	69	65		0
2008	67	32	84	80	72		0
2009	78	47	83	82	75		0
2010	84	63	95	96	86		88
2011	95	80	95	95	92	96	92
2012	95	91	95	97	92	0	96
2013	96	91	96	96	99	96	96
2014	97	95	98	90	98		94
2015	97	95	95	96	98	96	94
2016	97	97	96	96	96		96
2017	98	98	96		98	96	98

Table 3. Insecticide applied on cotton fields in La Laguna, Mexico, before having Bt cotton as a control alternative against lepidopteran pests (1982–1989) and after 19 yr of use of Bt cotton

Insecticide	Years 1982–1989			Year 2016		
	Rate (kg AI/ha)	Environmental impact (field EIQ)[a]	Environmental impact (total EIQ)[b]	Rate (kg AI/ha)	Environmental impact (field EIQ)	Environmental impact (total EIQ)
Azinphos-methyl	0.600	27.2	75.67			
Beta cyfluthrin				0.045	1.5	1.5
Bifenthrin				0.050	1.9	1.0
Carbaryl	2.400	48.7	63.24			
Cyfluthrin	0.038	1.3	0.04			
Cypermethrin	0.100	3.1	2.73	0.100	3.1	1.6
Chlordimeform	0.750	40.2	2.15			
Chlorpyrifos	0.720	16.5	6.69			
Deltamethrin	0.013	0.3	0.25			
Diazinon	0.375	14.1	0.03			
Dimethoate	0.400	11.5	0.03	0.600	17.2	4.3
Endosulfan	0.700	23.1	1.40			
Fenvalerate	0.150	5.1	3.43			
Fluvalinate	0.072	2.3	0.01			
Imidacloprid				0.105	3.3	4.1
Lambda-cyhalothrin	0.035	1.4	0.03			
Malathion	1.500	30.6	17.65	0.950	19.4	131.0
Methidathion	0.600	16.8	2.91			
Methomyl	0.360	7.1	3.17			
Methyl parathion	0.720	21.7	141.69			
Profenofos	0.750	38.2	39.97			
Thiodicarb	0.563	11.2	0.22			
Triazofos	0.630	18.3	18.03			
Average	0.574	16.9	18.97	0.308	7.7	23.9
Average without including malathion	0.530	16.2	19.04	0.180	5.4	2.5

[a] Field EIQ, EIQ of one field application.

[b] Total EIQ, EIQ of all the applications in a crop season.

of the insecticide sprayed on the crop targeted the pink bollworm. Two years after the use of these cultivars in ~80% of the planted area, 1.6 *P. gossypiella* larvae per boll was the average in their fields; densities that have been greatly reduced, or nearly disappeared, with a high and constant adoption of Bt cotton (Table 2), and the use of a greater variety of effective measures within an integrated program. Due to the implementation of these measures for more than a decade, this pest is extremely hard to find in la Laguna (Table 4), and in other regions of Mexico, where this insect used to be of serious concern. Extremely low populations of *P. gossypiella* have benefitted farmers, adopters of Bt cultivars or not, and the environment, and consequently, it has prevented the continuation of the Bt-resistance monitoring program, due to the lack of insects in the field to perform susceptibility tests.

Table 4. Densities of *Pectinophora gossypiella* per cotton boll in La Laguna, Mexico

Year	*Pectinophora gossypiella* larvae per boll of conventional cotton	*Pectinophora gossypiella* larvae per boll of Bt cotton
1999	1.62	0.07
2000	0.04	0.006
2001	0.01	0.0005
2002	0.04	0
2007	0.03	0.001
2016	0	0

Before the establishment of the eradication program against *P. gossypiella* in 2014, a noticeable reduction of moths and larvae were already documented in La Laguna. Approximately 20% of the area planted with conventional cotton has also benefited in terms of less *P. gossypiella* pressure, putatively from the effect of having a greater control of this pest in Bt cotton fields, although other contributing factors such as plant antibiosis of newer cultivars, climate change, and better agronomic practices may have an influence on reducing pink bollworm populations. Other cotton-producing areas have experienced the same reduction on the overall populations of this pest. In Baja California, average number of larvae per boll decreased from 0.29 to 0 from 2007 to 2010, an absence of *P. gossypiella* in the region that has been maintained since 2016, when the last population evaluation took place. In Chihuahua, in 2002, ~15% of the conventional cotton plots were still infested with this pest, and by 2006 it was reduced to only 0.5% in conventional cotton, and by 2007 *P. gossypiella* has not been detected in either cultivars, conventional or Bt cotton. This trend of close to nonexistent *P. gossypiella* populations has been also observed with the data obtained from monitoring programs using a large number of pheromone traps that used to capture moths in Baja California, Chihuahua, La Laguna and Sonora (Fig. 2).

Once a serious menace for cotton production in many areas of Mexico, *Chloridea virescens*, the pest that brought notoriety to the

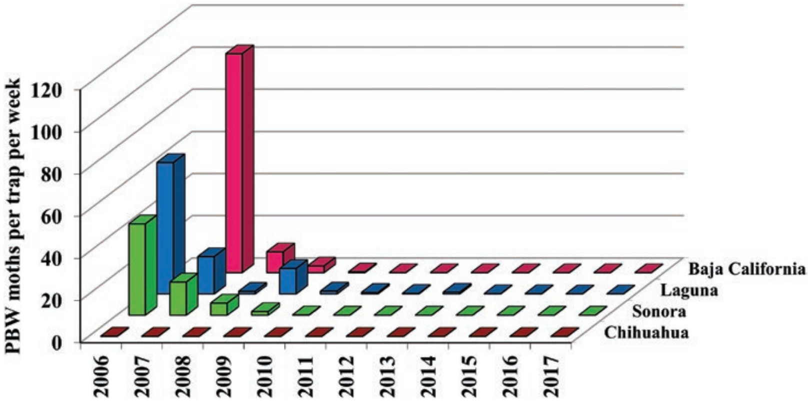

Fig. 2. Trend of moth captures in pheromone traps in four States of Mexico.

region (Metcalf and Luckmann 1994), has not been a threat for cotton production for the past two decades. In southern Tamaulipas this pest became highly resistant to a variety of synthetic insecticides, forcing growers to spray up to 5–6 times without achieving a satisfactory control (Terán-Vargas *et al.* 2005). A combination of factors, including a drastic reduction of the cotton area, and growers no longer applying insecticides against this pest once they switched to Bt cotton cultivars, restored its susceptibility to the most commonly used synthetic insecticides in a period of 2–3 yr after the adoption of Bt cotton (Terán-Vargas *et al.* 2005). It has been proposed that Bt cultivars have had a major impact on the population of *C. virescens* in North America (Blanco 2012), reducing the populations from 50,000 larvae per hectare in 2001 to 13,000 larvae per hectare in 2003, to almost nonexistent on cotton in the decade of 2010. However, *H. zea* continues to be a troublesome pest in cotton in southern Tamaulipas, while in La Laguna, an area of high maize production, the densities of *H. zea* have diminished greatly.

A single tool for the management of problematic pests has made a great difference for the environment and the cotton producer. For example, Bt cotton in Mexico, and elsewhere, has helped growers and crop advisors by reducing the drudgery of scouting for hard to find *H. zea* and *C. virescens* eggs and small larvae in a large number of cotton plants. Because very low action thresholds have been recommended for these pests (one small larva per ~10 plants), it has made imperative a constant vigilance for an increasing pest pressure. Scouting for *P. gossypiella* larvae inside bolls, no longer necessary in pink bollworm-free areas, requires that growers/crop advisors collect up to hundred 15- to 25-d-old bolls to inspect them for the presence of small larvae or signs of damage in each field, a time-consuming and costly practice. Time devoted to estimate very low number of pests in a field also increases costs, but never reduces the preoccupation of growers. Scouting for the presence of *H. zea* and *C. virescens* larvae on cotton differs from *P. gossypiella*. These two pests move around the cotton foliage for a number of days until they are large enough to penetrate a cotton boll and reside in it for a few days. Foliar sprayed insecticides can be effective at controlling this pest complex by direct contact with the pesticide on the foliage. The difference with *P. gossypiella* is that very small larvae can penetrate the cotton boll wall and become established inside for the rest of their immature development, and such behavior prevents them from coming in contact with a foliar-applied insecticide. The introduction of Bt cotton cultivars in Mexico alleviated some of this scouting at least for *C. virescens* and *P. gossypiella*, but the possible presence of *H. zea* still requires some scouting in a few Mexican cotton regions. Bt cotton produces Bt-toxins that effectively control these three pests inside and outside cotton bolls, therefore, the grower and crop advisor are no longer as anxious as they used to be, not checking their fields constantly to detect incipient populations of these lepidopteran pests. More than 100 yr ago two cotton entomologists wrote '…the discovery of a poison that would be safer under all conditions of weather and of application, and one that would at the same time give the greatest budworm control, was much to be desired' (Morgan and McDonough 1917). Bt cotton not only delivers those considerations but has allowed the implementation and advancement of integrated pest management and insecticide resistance management to unprecedented levels for a row crop.

Table 5. Average yields (bales per hectare) in selected Mexican cotton regions at the time of introduction of Bt cotton (≤1996), and two decades later

Year	Baja California	Chihuahua	La Laguna
≤1996	4.4	4.9	3.5
1998–2010	6.3	7.3	5.4
2016	8.7	7.9	7.0

Impacts of Bt Cotton on Crop Yields

Mexican cotton growers have experienced a well-deserved increase in their yields by combining several successful strategies that include better agronomic management of the crop, cotton cultivars adapted to their needs, and an integrated pest management program that relies on the effectiveness of Bt cotton against Lepidoptera. The results of these tactics have maintained very high cotton yields in the country, and a notable yield increase that is reflected in Table 5.

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