Fourteen Years of *Bt* Cotton Advances IPM in Arizona

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Abstract. The pink bollworm, *Pectinophora gossypiella* (Saunders), first invaded Arizona in 1926 and has been a key pest of cotton, *Gossypium hirsutum* L., since the early 1960s. A broad range of tactics has been developed to manage this pest including a variety of cultural methods, mating disruption via pheromones, sterile insect release, and plant resistance. Transgenic cotton producing the insecticidal proteins of *Bacillus thuringiensis* Berliner (*Bt*) was introduced in 1996 and was rapidly and widely adopted by producers in Arizona. Adoption rose to approximately 86% by 2006 and has been more than 93% since 2007 when the state was granted a U.S. Environmental Protection Agency exemption to eliminate required refuge plantings as part of a regional eradication program. The deployment of *Bt* cotton for selective control of caterpillars led to dramatic regional reductions in abundance of pink bollworm, and associated crop damage and insecticide use. *Bt* cotton has also been a key technology enabling more selective and biologically-based control approaches for sweetpotato whitefly, *Bemisia tabaci* (Gennadius), and western tarnished plant bug, *Lygus hesperus* Knight, two other keys pests of cotton in Arizona. Overall insecticide use (statewide average number of sprays per hectare) in cotton has dropped 88% since 1995. Some challenges ahead include re-invasion of eradicated zones, maintaining susceptibility of pink bollworm to *Bt* cotton, the economics of *Bt* cotton use in a post-eradication future, and a rapidly changing agroecosystem.

Resumen. El gusano rosado, *Pectinophora gossypiella* (Saunders), invadió por primera vez Arizona en 1926 y ha sido una de las plagas principales del algodonero desde principios de los 1960s. Una amplia variedad de tácticas se han implementado para controlar a esta plaga, las que incluyen métodos de cultivo, la disrupción de apareamientos debido a la presencia de feromonas, la liberación de insectos estériles, así como variedades resistentes. El algodonero transgénico que expresa *Bacillus thuringiensis* Berliner (*Bt*) fue introducido en 1996 y fue rápidamente adoptado por los agricultores de Arizona. Esta adopción se incrementó el 86% en 2006 y a partir del 2007 ha llegado a 93%, cuando al estado se le otorgó la excepción por parte de la institución a cargo de la protección del medio ambiente Estadounidense (U.S. Environmental Protection Agency) para eliminar el refugio, como parte de un programa de erradicación regional. La utilización de algodonero *Bt* para el control de ciertos gusanos ha llevado a una

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reducción dramática a nivel regional de las poblaciones de gusano rosado, el daño al cultivo y el uso de insecticidas. La tecnología algodonero *Bt* ha sido fundamental para que tácticas de control más selectivas y con bases biológicas se hayan podido también implementar para el control de *Bemisia tabaci* (Gennadius) y *Lygus hesperus* Knight, dos plagas de mucha importancia en Arizona. La reducción general del uso de insecticidas en el algodonero (promedio estatal del número de aplicaciones por superficie) ha sido del 88% desde 1995. Los retos que quedan pendientes incluyen la re-invasión de zonas donde ya se erradicó esta plaga, el mantener la susceptibilidad del gusano rosado al algodonero *Bt*, el análisis económico del uso del algodonero Bt en el futuro después de la erradicación de *P. gossypiella,* y los rápidos cambios del agroecosistema.

The pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), has been a key pest of cotton, *Gossypium hirsutum* L., in Arizona and the low desert valleys of southern California since the mid 1960s. Saunders first described the pink bollworm in 1842 from specimens infesting cotton in India. Since that time the insect has invaded most cotton-producing areas of the world, mainly through movement of infested cottonseed. Texas was its first landfall in the U.S. in 1917. Pink bollworm was found in eastern Arizona by 1926, and the main cotton-producing region of central Arizona 3 years later (Spears 1968, Noble 1969). Despite repeated attempts to eradicate the pest in Arizona and elsewhere in the early to mid 1900s through regulatory measures and pest control programs, the pink bollworm became established in the western U.S. by 1965 (see Henneberry and Naranjo 1998). These events are a reminder of the resiliency of this pest as the latest eradication attempt is nearing completion in Texas, New Mexico, Arizona, California, and the northern bordering states of Mexico (National Cotton Council 2001).

The pink bollworm is functionally a monophage of cotton. Its host range spans ≈70 species of plants in seven families including okra, *Abelmoschus esculentus* (L.) Moench, the only other cultivated crop of note hosting pink bollworm in the U.S. (Noble 1969, Ingram 1994, Henneberry and Naranjo 1998). The insect prefers cotton; other weedy and wild hosts are not considered important in its seasonal population dynamics (Noble 1969). Pink bollworm feeds on reproductive structures of the cotton plant, completing the first generation in flower buds and as many as four additional generations on seeds within the fruit (bolls). This feeding introduces pathways for contamination (e.g., aflatoxins) and destroys lint production, leading to significant economic damage. Between 1979 (when statewide damage estimates were initiated) and 1995, pink bollworm were responsible, on average, for 0.05-4.5% damage to cotton yields (1.2-74.8% of insect-related yield losses) and accounted for up to 60% of all insect control costs and $48.5 million in yield loss and control costs annually (Ellsworth et al. 2007). The introduction of transgenic cotton producing the Cry proteins of *Bacillus thuringiensis* Berliner dramatically changed these economic patterns.

The pink bollworm has been an extensively studied pest (Naranjo et al. 2002), and a wide array of tactics has been developed for integration into pest management programs (reviewed by Henneberry and Naranjo 1998). Pupating and diapausing larvae are subject to adverse climatic and biological factors leading to high levels of mortality. Most stages of the insect are protected from natural enemies, but various predators attack pink bollworm, and Naranjo and Hagler (1998) estimated that ≈20% of eggs are killed by predation. A suite of cultural methods can effectively control pink bollworm by enhancing suicidal emergence of adults by delayed planting, and by short-season production systems and rapid plow-down that interrupt diapause in the final generation of the season, thus reducing the number that overwinter (Henneberry 1986). This strategy was successfully demonstrated in Imperial Valley, CA, where short-season production initiated in 1989 reduced pink bollworm abundance while enhancing yields from 1990-1994 (Chu et al. 1996). Insecticides are commonly used, but timing is critical because the strategy is to target female moths before they lay eggs. Insecticides are rarely more than 50% effective (Ellsworth unpublished data) and newer insecticides that target feeding lepidopteran larvae are ineffective because larvae live within bolls. Mating disruption through application of sex pheromones can be effective, particularly when moth abundance is low during early season (Henneberry et al. 1982, Staten et al. 1987). Sterile-insect release has played a role in excluding pink bollworm from the San Joaquin Valley of California during the past 3-4 decades (Henneberry 1994). Cultural controls, insecticides, mating disruption, and sterile-insect release, along with *Bt* cotton, are the primary components of the eradication program.

Transgenic cottons producing the insecticidal proteins of *B. thuringiensis* (*Bt*) were first commercially planted in Australia, Mexico, and the U.S. in 1996. Adoption was rapid, and by 2009, *Bt* cotton was grown in 11 countries. The three largest cotton producers in the world, China, India, and the U.S., have very high adoption rates (63-87% in 2009) contributing to about 50% of the global cotton area planted to *Bt* cultivars (James 2009). Adoption in Arizona was initially constrained in 1996 by seed supply, but rates expanded quickly to 64% in 1997 and 86% by 2006 (Table 1). Adoption rates nearing 100% from 2007 onward have been driven by an exemption by U.S. Environmental Protection Agency for the normal refuge planting requirements of non-*Bt* cotton to augment the eradication program (Antilla and Liesner 2008).

The effects of *Bt* cotton production on target pest populations and damage potential have been dramatic. Carrière et al. (2003) measured the impact of *Bt* cotton cultivation on regional suppression of pink bollworm. Similar large-scale suppression has been observed for target pests of other *Bt* crops (Adamczyk and Hubbard 2006, Hutchison et al. 2007). For example, high rates of *Bt* cotton adoption in northern China led to wide-scale suppression of *Helicoverpa armigera* (Hübner) (Wu et al. 2008) with the beneficial side-effect of reducing abundance of this polyphagous pest in other crops such as maize, *Zea mays* L.; peanuts, *Arachis hypogaea* L.; soybeans, *Glycine max* L.; and various vegetables. On the contrary, Lu et al. (2010) suggested that large-scale reductions of insecticides on *Bt* cotton in China may now be associated with increasing abundance of various plant bugs.

Bt cottons producing Cry1Ac or Cry1Ac plus Cry2Ab2 proteins are efficacious against pink bollworm, providing almost 100% control (Ellsworth et al. 2002). Therefore, losses to pink bollworm and associated insecticide use in Arizona are restricted to non-Bt cotton. With adoption rates nearing 100% since 2007 and eradication almost complete, overall damage to cotton by this pest has been eliminated (Table 1). Decline in insecticide use for pink bollworm has paralleled the trend for crop damage. On average statewide for the whole cotton crop, almost seven applications per hectare were made for pink bollworm in 1990, an outbreak year, but reductions in number of sprays decreased to less than one in 1997 and has been essentially, if not, zero since 2007. Moreover, insecticide use in *Bt* cotton has averaged about 0.5 (range 0-1.4) sprays per hectare less than non-*Bt* cotton since 1999 even after accounting for the elimination of pink bollworm sprays, thus indicating the synergistic effect of the technology on total pest control (not shown).

Bt cotton is highly selective and numerous studies in Arizona and other parts of the world have demonstrated negligible effects on non-target arthropods, including natural enemies (Naranjo 2005a,b; Cattaneo et al. 2006; Sisterson et al. 2007; Wolfenbarger et al. 2008). Enabled by this selectivity and supported by a truly integrated program, the benefits of *Bt* cotton have cascaded to controlling other

Table 1. *Bt* Cotton Adoption Rates, Yield Losses Caused by Pink Bollworm (PBW), and Insecticide Applications for PBW and All Arthropod Pests, 1990-2009 in Arizona[a]

Cuadro 1. Tasa de Adopción del Algodonero *Bt,* Pérdidas de Producción (Yield Losses) Debidas al Gusano Rosado (PBW), y Aplicaciones de Insecticida (Sprays per Hectare) para el Control de PBW y Otras Plagas de Artrópodos en Arizona durante 1990-2009

		Yield loss (%)[b]			Sprays/hectare[b]			
Year	% *Bt* cotton	Non-*Bt*	*Bt*	Total[c]	PBW (non-Bt)	PBW (Bt)	PBW (total)[c]	All pests[c]
1990	0	-	-	4.49			6.8	11.4
1991	0	-	-	0.93			2.5	9.8
1992	0	-	-	0.73			1.1	7.7
1993	0	-	-	0.05			0.1	3.8
1994	0	-	-	3.85			2.9	9.0
1995	0	-	-	1.19			2.9	12.5
1996	11[d]	-	-	2.77			1.7	5.7
1997	64[d]	-	-	2.63			0.9	5.3
1998	57[d]	-	-	0.80			0.4	4.7
1999	65	2.55	0.18	0.99	0.9	0.03	0.3	1.9
2000	64	3.23	0.00	1.14	1.6	0.0	0.6	2.8
2001	68	3.85	0.00	1.23	1.3	0.0	0.4	3.1
2002	68	2.40	0.00	0.96	1.7	0.0	0.7	3.3
2003	74	2.26	0.03	0.61	1.6	0.0	0.4	4.3
2004	73[e]	2.83	0.04	0.58	1.6	0.0	0.3	2.7
2005	74	2.45	0.01	0.65	2.5	0.02	0.7	4.9
2006	86	2.26	0.00	0.28	0.5	0.0	0.1	1.4
2007	93	0.33	0.00	0.02	0.1	0.0	0.01	1.4
2008	98	0.005	0.00	0.00	0.0	0.0	0.0	1.7
2009	98	0.00	0.00	0.00	0.0	0.0	0.0	1.7

[a]Compiled from Ellsworth et al. 2007 (rev. 2010) for upland cotton [Recopilado de Ellsworth et al. 2007 (rev. 2010) para algodonero upland].

[b]Separate records for non-*Bt* and *Bt* cotton were not collected until 1999 [Datos por separado entre algodonero *Bt* y No-*Bt* se empezaron a registrar a partir de 1999].

[c]Estimates for non-*Bt* and *Bt* cotton acreage combined [Estimado de combinar la superficie del algodonero *Bt* y No-*Bt*].

[d]Estimates derived from USDA-AMS survey of market share by variety [Estimado proveniente del censo USDA-AMS de la proporción de mercado por variedad].

[e]Estimate derived from Monsanto sales records [Estimado derivado de los datos de ventas de Monsanto].

pests in the Arizona cotton system. In 1996, a bellwether year in the state, not only was *Bt* cotton introduced, but a robust IPM program was brought online that allowed growers to make rational decisions about the need for controlling sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Ellsworth and Martinez-Carrillo 2001, Naranjo and Ellsworth 2009a). The central component of this IPM system was the preservation of natural enemies through the use of highly selective insecticides and a simple decision protocol. Natural enemies, particularly insect predators, inflict high levels of mortality on whitefly populations if left undisrupted by broad-spectrum insecticide (Naranjo and Ellsworth 2009b). The key contribution of *Bt* cotton was the elimination of such broad-spectrum sprays for pink bollworm, particularly the common early-season sprays intended to extend suicidal emergence (Ellsworth and Meade 1994). That success was followed by the adoption of selective insecticides to control western tarnished plant bug, *Lygus hesperus* Knight (Ellsworth and Barkley 2005). Altogether, insecticide use in Arizona cotton has been driven to historical lows during the last 4 years (Table 1), enabled, in part, by the large-scale use of *Bt* cotton. These transformational changes in cotton production have been witnessed globally. Brookes and Barfoot (2010) estimated that *Bt* cotton production worldwide has reduced insecticide active ingredient by more than 140 million kg between 1996 and 2008.

Still, even with the success of *Bt* cotton and the overall cotton IPM program in Arizona, challenges remain. As the pink bollworm eradication program winds down in the next few years and enters the post-eradication era, constant vigilance will be needed against re-invasion. The history of this pest in the U.S. and elsewhere has taught us that the pink bollworm is resilient and we cannot become complacent. Continued susceptibility of pink bollworm to Cry proteins is crucial (Tabashnik et al. 2005) because *Bt* cotton will likely remain a key component in the near-term, post-eradication era where it could function as a hedge to decades of future investment in sterile insect release as the exclusive exclusion technology. At the same time, growers will want to shed the technology fee associated with *Bt* cotton in due course even as the development of new elite germplasm is increasingly centered strictly on *Bt* varieties. Ultimately, Arizona growers will be faced with an economic decision of deploying a less-than-useful gene in the newest and best varieties, or older and perhaps less productive non-Bt lines. Further, two of the three keys pests of Arizona cotton (sweetpotato whitefly and pink bollworm) are exotic, invasive species and the threat of invasion of new insect pests or new diseases (e.g., whitefly-transmitted cotton leaf curl virus) is constant. Finally, the changing face of agriculture, particularly in the western U.S., has direct and indirect effects on cotton production and IPM. Cotton production has been declining in the west during the past decades and new crops as well as changing distribution of existing crops has the potential to alter the agroecology in ways we cannot always predict.

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