Pink Bollworm Resistance to *Bt* Cotton and Management Considerations

Dr G. M. V. Prasada Rao, Dr Sandhya Kranthi[1] and Dr Keshav Kranthi[2]

Dr G. M. V. Prasada Rao, PhD, Principal Scientist (Entomology), ANGRAU, LAM, Guntur, Andhra Pradesh, India, has 20 years of research and extension experience in cotton. He published 60 peer-reviewed research papers and four books/manuals. Dr Prasada Rao bagged 16 recognition awards including the prestigious National Award "Dr. Bap Reddy Memorial Award" for contributions in the field of IPM. He handled 200 lakhs worth externally funded research and extension projects. Dr Prasada Rao guided ten postgraduate and Ph.D. students in cotton Entomology. As a Course Director, he conducted an ICAR sponsored Winter School on IRM. Dr Prasada Rao is a member of ten professional scientific societies and the Fellow of Plant Protection Association of India.

Pink Bollworm Incidence Was Low in India Before the *Bt* Era

Interview with Dr GMV Prasada Rao

How serious is the problem of pink bollworm in AP? What could be the range of economic damage (%)?

Andhra Pradesh is one of the important cotton-growing southern states in India. The Pink bollworm, *Pectinophora gossypiella* attacks cotton late in the season. Of late, the PBW has become a major production constraint on cotton. Yield loss ranged from 20-50%. Around 50% damage to seed cotton was observed in some intensive cotton-growing blocks or mandals of the Guntur, Krishna, and Prakasam district of AP during 2020-21. Further, the damage was observed in October-November months onwards itself (2nd picking).

How serious was the pink bollworm in earlier times compared to what it is in recent years?

Pink Bollworm incidence was low before Bt era. Before *Bt*, the incidence was low in Andhra Pradesh. After *Bt* also till 2007-08, incidence was low and economic damage was not much since it was causing sporadic damage to final harvests. From there to 2014-15 incidence was almost nil in AP. However, since 2015-16 season again it started appearing and caused severe damage during 2017-18 and 2020-21.

What do you think are the factors that prompted its recent resurgence as a serious pest?

- Widespread cultivation of long staple *G. hirsutum Bt* hybrids (>99% of the cotton area is under *Bt* hybrids).
- Continuous sowing and availability of cotton in different regions of AP (Round the year)
- Non-practice of stipulated IRM/IPM strategies
- Development of resistance in PBW against *Bt* hybrids

What could have prompted the rapid development of PBW resistance to Bt-cotton?

- High selection pressure due to extensive cultivation of only one or two *Bt* events.
- Monophagous nature of the pest
- Non-practice of the refuge strategy

Have there been any recent innovations for PBW management from research institutes?

- Efforts are in progress. Nonetheless, results of on-farm trials on Mass-trapping indicated positive in management of the pest. Likewise, mating disruption technology also promising.

What in your opinion are the most important management strategies?

- Practice of Dead or Closed period for 120-150 days (practically no cotton cultivation between seasons)
- Aggressive promotion of Pheromone technology: Mass trapping / Mating disruption
- Strict implementation of IRM/IPM on a community basis involving all the stakeholders.
- Cultivation of different short duration *Bt* cotton varieties/hybrids.

1) Project Consultant, International Cotton Advisory Committee, Washington, DC, USA
2) Chief Scientist, International Cotton Advisory Committee, Washington, DC, USA

Introduction

Genetically modified cotton (*Bt* cotton) was cultivated in 12.3 million hectares (ha) in India during 2020, which is 95% of the total cotton area of 12.9 million ha grown in the country. An estimated 9.8 million cotton farmers adopted *Bt* cotton technology. Studies show that *Bt* cotton is still providing good protection against *Helicoverpa armigera* and *Earias* spp. in the country. The studies also align with the fact that as of now there are no field level complaints of economic damage or development of practical resistance in *H. armigera* and *Earias* spp to *Bt* cotton in India. However, increase in resistance allele frequency to Cry1Ac was documented in field-collected population of *H. armigera* from Telangana and Andhra Pradesh in India. The combined allele frequency during 2013 and 2014 was 65 times and 29 times higher than the initial frequency recorded during 2004 (Kukanur *et al*., 2018), respectively. On the other hand, severe field incidence of pink bollworm (PBW) was noticed in some central (Gujarat and Maharastra) and Southern (Telangana and Andhra Pradesh) cotton-growing regions (Kranthi 2015 and Mohan 2017). Dhurua and Gujar 2011 confirmed field-evolved resistance to Cry1Ac in PBW populations collected from Gujarat. Further, Chinnababu Naik *et al*., 2018 conducted extensive resistance monitoring studies in PBW populations from 2010-2017 in 38 districts of 10 major cotton growing states of India and concluded that the PBW populations developed resistance to Cry1Ac and Cry2Ab in major intensive cotton growing districts of Central and South India. The *Bt*-resistant pink bollworm larvae have been causing considerable economic damage that led to panic in the Indian and Pakistani cotton sectors. The concerns were serious because not only did yields decline but the fibre quality deteriorated significantly enough to warrant a reduction in the market price of the 'poor quality PBW damaged cotton'. Strangely, this problem is unique to India and Pakistan and not in any other *Bt* cotton growing country in the world. Interestingly, all major cotton growing countries have been able to control PBW with *Bt*-cotton. Tabashnik and Carriere, 2019 reviewed the global resistance monitoring data and indicated that resistance management strategies adopted by three major cotton growing countries in the world; the USA, China and India had significant impact on the interaction of *Pectinopora gossypiella* with *Bt* cotton. Integrated Pest Management holds a crucial role in the management of this important pest on cotton in India (Kranthi, 2015 and Tabashnik, 2019). This paper discusses the status of insect resistance to *Bt* cotton in India and possible reasons for the development PBW resistance in India — why the situation is unique to India — and discussed different Integrated Pest Management recommendations for sustainable cotton production India.

Status of insect resistance to *Bt* cotton in India

Helicoverpa armigera

Kranthi (2012) reported that resistant ratios up to 31-fold were recorded in the populations tested from 2008/09 to 2010/11; 51-fold in one location from 2011/12 and 128-fold in two locations in 2016 (Kranthi, unpublished data). He stated that, *Bt* cotton continued to be effective against *H. armigera* even in those regions where highest RRs of 128-fold were observed. Survival of *H. armigera* populations on *Bt* cotton and field failures were not observed from any cotton growing region of India. Kukanur *et al*., 2018, reported an increase in resistance allele frequency to Cry1Ac in field collected populations of *H. armigera* from southern states of India; Telangana and Andhra Pradesh. The combined allele frequency during 2013 and 2014 was 65 times and 29 times higher than the initial frequency recorded during 2004, respectively. Singh et al (2021) reported Cry1Ac resistance allele frequencies of 0.050 (95% CI 0.022–0.076) and 0.056 (95% CI 0.035–0.075) in *Helicoverpa armigera* populations collected from pigeon pea grown alongside *Bt* cotton in 2016 and 2017 in the Telangana state of India. They stated that the resistance allele frequencies to Cry1Ac in the cotton bollworm remained unchanged compared to their earlier studies conducted in 2013 and 2014. Thus, Indian populations of *H. armigera* appear to be still susceptible to *Bt* cotton (Cry1Ac) at the field level.

Pectinophora gossypiella

Chinnababu Naik *et al*., 2018 reported negligible larval incidence of PBW on *Bt* cotton in North India. But, in Central and South India larval recovery in *Bt* cotton ranged from 29 to 72% during 2014-2017. Likewise, the mean Resistance Ratio (RR) for Cry1Ac was 47 (18-127) during 2013 and increased to 1387 (704-2060) during 2017. A similar increasing trend was observed for Cry 2Ab with a mean RR increase from 5.4 (1-31) in 2013 to 4196 (1306-9366) in 2017.

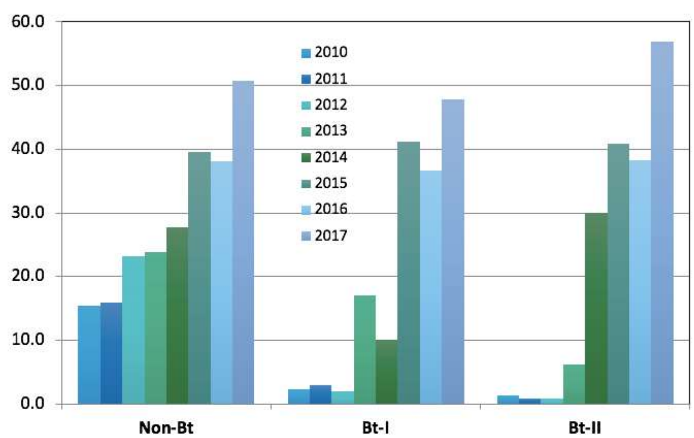

Figure 1. Increased levels of PBW infestation from 2010 to 2017 due to resistance development

Tabashnik and Carriere, 2019, reviewed the global resistance monitoring data and indicated that resistance management strategies adopted by three major cotton growing countries in the world; the USA, China and India had significant impact on the interaction of *Pectinopora gossypiella* with *Bt* cotton. They primarily pointed that abundance of refuge varied among these three countries that might have played a key role in the striking differences in the incidence of the same pest species on the same crop and on the same toxins, without discounting the role of other differing factors like nature of hybrids and varieties, climate and production practice adopted in the three major cotton growing countries in the world. Further, PBW populations in all the three countries contain cadherin mutations responsible for Cry1Ac resistance (Morin *et al.*, 2003, Fabrick *et al*., 2014 and Wang *et al*., 2019) and ABC transporter mutations in population of the USA and India conferring resistance to Cry2Ab (Mathew *et al*., 2018).

Possible causes for the recent PBW resurgence

The emergence of PBW as a monstrous pest of cotton in recent years in India is unprecedented. PBW was a serious pest for a long time in India mainly because of the long season which enabled the pest to thrive for several overlapping cycles, multiply and reinfest. The pest was relegated to a minor status soon after 1980 with the advent of short season varieties coupled the introduction of synthetic pyrethroids. After a hiatus of almost 30 years, PBW emerged as a major pest again after 2010, and this time more severely on *Bt* cotton, which was supposed to keep it under check. Its reappearance as a major pest in recent times appears to have been a result of six major factors (Kranthi, 2015) that are listed below:

Development of PBW resistance to *Bt*-toxins

Pink bollworm populations developed resistance to Cry1Ac and Cry2Ab and are thus able to survive and multiply on *Bt*-cotton to cause extensive crop damage.

The use of *Bt*-hemizygous hybrids

Studies (Kranthi, unpublished) showed that PBW survival was higher in *Bt*-hemizygous hybrids compared to *Bt*-homozygous varieties. This could have been due to low toxin expression and the presence of Bt-toxin segregation in developing bolls. The *Bt*-hemizygous hybrids had a low dose of *Bt*-toxins in developing fruiting parts thereby accelerating resistance. Younger developing stages such as square buds, flowers and developing younger bolls were found to have low *Bt* toxin levels that may have helped the heterozygous-resistant PBW to survive better. The seeds present in bolls of the *Bt*-hemizygous F-1 *Bt* cotton Bollgard-II (2-gene) hybrids segregate in 9:3:3:1 ratio for the cry1Ac and cry2Ab genes. The segregation ratios mean that about 6% of seeds do not contain any *Bt* toxin, 56% of seeds contain a mix of Cry1Ac and Cry2Ab, 19% of seeds contain Cry1Ac and the rest of 19% contain Cry2Ab. Thus, the seeds in a single boll at a time contain the two toxins in different ratios and different toxin titres (Kranthi, unpublished data) that helps PBW larvae to survive and develop resistance more rapidly because of the possibility of heterozygous-*Bt*-resistant larvae being able to survive on non-*Bt* seeds and the low-dose toxin seeds.

The return of long season cotton

The introduction of long season *Bt*-cotton hybrids provided a long season survival opportunity. The long season hybrid cotton varieties served food for PBW survival directly for a long period over the season and the multiplicity of hundreds of *Bt*-cotton hybrids which have overlapping flowering and fruiting cycles especially when sown in a long-staggered sowing window helped the pest to survive additional cycles that resulted in higher pestilence. A large number of hybrids with varying flowering and fruiting regimens provide continuous food for PBW in an overlapping manner over a long period to enable a greater number of generation cycles in the longer season, and thus a larger residual population flow into the subsequent seasons. Early sown (April-May in central India) crop in some regions starts flowering and reaches a peak flowering stage that coincides with the first minor seasonal PBW peak pink bollworm that occurs in July, thereby providing food for an otherwise suicidal population. Almost all the *Bt*-cotton cultivating countries in the world cultivate Bt cotton varieties except India which grows *Bt* cotton hybrids, that are grown for a longer duration of 180 to 240 days, thereby serving as continuous hosts for PBW.

Lack of adequate refuge hosts

The recommendation of 20% non-*Bt* cotton to be grown as five border rows was not easily accepted by Indian farmers because of poor quality non-*Bt* seeds supplied by many seed companies and the fear of suffering losses due to bollworm infestation in the 20% refuge non-*Bt* crop. In hindsight, it appears that the recommendation was not practical. PBW is functionally monophagous on cotton with few alternative hosts in the cotton cropping systems. Therefore, resistance development seems to have been inevitable due to a strong selection pressure in the absence of non-*Bt*-cotton or other non-*Bt* host crops that may have otherwise slowed down resistance development as refuges.

The synthetic pyrethroid factor

It is widely believed that the introduction of synthetic pyrethroids in 1980 resulted in a significant decline in the PBW pest status in India. PBW showed signs of resistance to synthetic pyrethroids by mid-nineties, but not strong enough to warrant control failures. Bollworm resistance to pyrethroids and introduction of *Bt*-cotton led to a decline in insecticide usage during 2002 to 2007, especially to a significant reduction in pyrethroid usage across India which may have allowed the pest to survive better.

Ignoring IPM

Bt cotton is meant to control all three bollworms. Farmers were told that the technology would effectively control all three bollworm species including pink bollworms. Thus, there was a general notion that bollworms would be controlled by *Bt* cotton and farmers were expected to take care of sap-sucking insect pests. Consequently, integrated pest management (IPM) methods were mostly oriented toward sucking pests and not toward bollworms. In effect, IPM for bollworms was completely ignored. It was only after the emergence of PBW resistance to *Bt* cotton that seed companies and the technology developers of *Bt* cotton started reiterating the importance of IPM in bollworm management.

Why pbw resurged in India & Pakistan but not in China & USA

Pink bollworm is a global pest. While PBW emerged as a major pest recently in India and Pakistan, it continues to maintain a low profile in other countries where it was once a very serious pest. India opted for *Bt*-cotton hybrids, whereas Pakistan like rest of the world chose to grow *Bt*-cotton open-pollinated varieties (OPV). India grows Bollgard-II® *Bt*-cotton which has two *Bt*-genes *cry1Ac* and *cry2Ab*, whereas Pakistan continues to depend on Bollgard® *Bt*-cotton which expresses a single *Bt* gene *cry1Ac*. But despite the differences in hybrid v/s OPV and the single gene v/s two genes, PBW emerged as a major pest in both countries.

Two main factors may have influenced higher levels of PBW pestilence in India and Pakistan. PBW survives better in both countries because it developed resistance to *Bt*-cotton. The second factor pertains to the long season cotton in both countries. While *Bt*-hybrids grown at a low density in India warrant a longer season for a harvest of decent yield, *Bt*-varieties grown a higher density as in Pakistan do not need to be grown over a longer season. However, the sowing window in Sindh province of Pakistan extends over a long period of almost four months from mid-March to mid-June. Thus, Pakistan has a shorter gap of only three to four months of a closed-season or a cotton-crop-free period; a situation that is similar to India.

The cotton crops in USA, China, Brazil, Australia, Turkey etc., are grown for five to six months, thus allowing a 'closed-season' of six months.

USA

The United States initiated a successful science driven campaign to eradicate pink bollworm. The cotton growing season continues to be restricted to 5-6 months. Apart from implementing a suite of cultural methods, scientists helped farmers ensure a strong compliance of non-*Bt* refuge cultivation. Scientists also coordinated mass releases of sterile PBW moths that helped to minimise populations and deployed pheromone technology for monitoring and mating confusion. USDA worked closely with the Mexican government to implement the programme jointly. Mexican Government agencies (SAGARPA and SENASICA) and United States (USDA) together with scientists chalked out plans meticulously and executed them to near perfection over fifty years to eradicate the pink bollworm. The key components of the eradication programme were pest surveys using delta traps, sterile insect technique, pheromone-based mating confusion, short season and transgenic Bt cotton. Mating confusion was through PBW Rope technology used at 500 ropes per hectare as one or two applications or 4-5 pheromone sprays of NoMate or CheckMate per season. Two sterile moth rearing facilities were established in Harlingen, Texas and Phoenix, Arizona in 1968 and 1969 and a new facility in a building of 6131 square metres was developed in Phoenix in 1995. Sterile insect releases started in 1968 in California and have continued ever since. It is worth mentioning that by 2005, the Phoenix rearing facility was producing 20 million to 28 million moths per day. The sterile moths were labelled with Calco red oil food dye or strontium and tracked diligently. Thus, cotton remains PBW-free in the USA because of a combination of IPM and IRM technologies. Bt-cotton technology also played a major role in PBW eradication.

Bt-cotton varieties in the USA express a range of *Bt*-toxins which makes it relatively difficult for bollworms to develop resistance to all the *Bt*-toxins. The availability of different *Bt* cotton varieties for technology durability and improved insect resistance; Bollgard® 1 containing Cry 1Ac, Bollgard® II with Cry1Ac + Cry2Ab, Widestrike™ with Cry1Ac + Cry1F, Widestrike® 3 contains Cry1Ac, Cry1F and VIP3a, Bollgard® 3 containing VIP 3a along with Cry1Ac and Cry2Ab, Twinlink® Cry1Ab and Cry2Ae, Twinlink® plus containing Cry1Ab, Cry2Ae along with VIP3Aa19.

China

In China, farmers continue to depend on cry1Ac based *Bt*-cotton which in some varieties is pyramided with a protease inhibitor gene. Bollgard II cotton is not grown in China. Farmers cultivated F_2 hybrid seeds from crosses between *Bt* and non-*Bt* cotton, producing 25% non-*Bt* plants which acted as refuge in *Bt* cotton. Seed mixtures generated with F_2 hybrids in China were found to have been effective in delaying PBW resistance development against *Bt*-cotton. In 2011-2015, F_2 hybrid fields accounted for a mean of 67% of the total cotton cultivated and PBW population was reduced by 96% & insecticide sprays were reduced by 69% compared to 1995-1999 (non-*Bt* era) (Wan *et al*., 2017). Further, cultivation of short season cotton also might have a role in delaying the development of resistance to the pest (Dai and Dong 2014).

PBW management strategies

A range of management strategies, especially for Indian conditions, have been proposed by Kranthi (2015). A short season coupled with a closed season of 5-6 months plays a crucial role in the management of cotton bollworms especially pink bollworm. Other technologies such as pheromones for monitoring, mating confusion and mass trapping, crop residue management, judicious nitrogen usage and diligent insecticide management contribute to minimise PBW populations and damage.

Fertiliser management

A long season crop is most vulnerable to PBW infestation. Excessive nitrogenous fertilizers create conditions for a long season crop through a combination of two effects. The first effect is direct wherein excessive nitrogen leads to excessive vegetation and delayed maturity. The second effect is indirect wherein excessive nitrogenous fertilisers cause higher susceptibility to sap sucking insects, which warrant the use of organophosphate and neonicotinoid insecticides, most of which cause delayed maturity of the crop. It is important to practice balanced application of NPK; avoid excess use of nitrogenous fertilisers and encourage the use of organic fertilizers.

Pesticide management

A few types of organophosphate and neonicotinoid insecticides are known to cause physiological changes in plants to delay crop maturity. Late maturity extends the season thereby enhancing vulnerability to PBW infestation and damage. Organophosphate and neonicotinoid insecticides are used for sucking pest management early in the season. Selection of sucking resistant/pest tolerant hybrids, helps to avoid spraying of insecticides such as monocrotophos, acephate, imidacloprid, thiomethoxam etc., during the early crop growth period; these chemicals delay crop maturity. Avoiding these chemicals helps in synchronous early maturity of the bolls resulting in less incidence of PBW. Though synthetic pyrethroids are effective in controlling PBW, their indiscriminate use can lead to resurgence of whiteflies and American Bollworm. Therefore, avoid spraying of synthetic pyrethroids until the economic threshold levels (ETLs) for PBW are reached late in the season. ETLs of 8 moths per pheromone trap per three consecutive nights are used for insecticide interventions. Though conventional insecticides such as thiodicarb, profenophos, quinalphos or chlorpyriphos 20% EC @ 500 ml/ac are recommended, recent studies show that chlorantraniliprole, emamectin benzoate, flubendiamide, spinosad and indoxacarb are also effective and have a better environmental profile compared to the conventional insecticides.

Cultural practices

Several cultural practices have been reported to be highly effective in PBW management. Practices such as removal of ratoon plants or rogue plants; flooding of fields after harvest to kill residual diapausing larvae and pupae in soil; removal and destruction of rosette flowers, dropped squares and pre matured bolls; crop rotation and deep ploughing to expose PBW diapausing larvae and pupae to birds and excessive heat were found to contribute to enhancing pest control efficacy. Maintaining a non-*Bt* refuge crop helps in delaying the development of PBW resistance to *Bt* cotton.

Crop residue management

Cotton crop residues and ginning mill waste harbour pink bollworm larvae and pupae (Novo and Gabriel, 1994). PBW larvae enter into diapause and can be found in seeds and other crop residues. Non diapausing larvae become pupae and the adults that emerge propagate their generations on crops such as okra, hemp, roselle or weeds belonging to Malvaceae, Fabaceae, Convolvulaceae and Euphorbiaceae. Crop residue management and ginning mill waste destruction play an important role in minimising carryover populations of the pink bollworm. The majority of diapausing pupae are expected to be present in late season bolls, especially the abandoned last lot of immature bolls. Strategies such as defoliation, removal of late season green bolls and desiccation of the crop at the end of season were found to be effective in reducing over wintering larvae in the US (Adams, 1995). Encouraging the practice of diligent sanitation in ginneries and fields helps in reducing the residual pest carryover. Allowing cattle to graze in fields after final harvest was found to be beneficial because these animals were found to feed on immature green bolls that were the main sources of pest carryover.

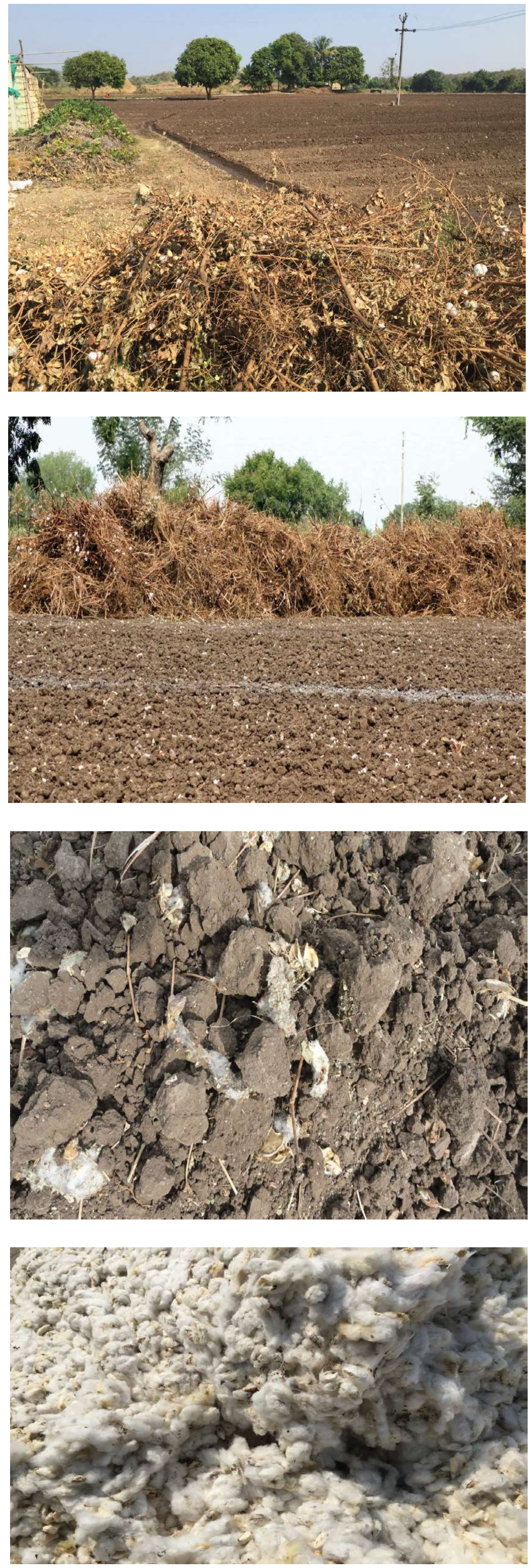

Figure 2. Immature unharvested residual bolls in stacks of cotton stalks, crop debris on soil and diapausing pupae in seed cotton at gins are sources of PBW carryover. (Photos: Kranthi)

Pest-crop synchrony management

There are two theories —namely early planting and late planting — that have been proposed for PBW management to create asynchrony between pest occurrence its food. Early planting could ensure that bolls mature before PBW occurrence and escape, because peak populations of PBW are known to occur only late in the season. Though, PBW is a late season pest it also occurs as a small peak early in the season that acts as a precursor of the ensuing populations. Late planting has been suggested as a strategy so that the early emerging PBW populations do not have access to any food supply and starve to death (Frisbie et al., 1989). Thus, PBW infestations could be greatly reduced in the absence of the early precursor populations. In both cases, whether early of late planting, the strategy of deploying short-season varieties that are terminated in time and crop residues are desiccated has been acknowledged to be effective in minimizing pestilence and pest carryover. *Bt*-cotton was able to resist PBW damage until the emergence of insect resistance. A few varieties have been reported to have a higher tolerance to pink bollworms in China (Wu, 1993; Wang et al., 1993).

Biological control

There are two parasitoids that have so far been effectively used in PBW management across the world. The egg parasitoids *Trichogramma bactrae* or *Trichogramma brasiliense* have been recommended @ 60000 eggs per acre at peak flowering period to enable the egg parasitisation. *Bracon kirkpatricki* is a larval parasitoid that can play an important role in PBW management, provided the naturally occurring populations are allowed to establish and proliferate and parasite populations are also augmented if and when necessary.

Figure 3. *Apanteles* parasites recovered from field collected PBW larvae

Figure 4. *Bracon* parasites recovered from field collected PBW larvae

Figure 5. Deformed per-pupa and pupa

Closed Season

A closed season is legally enforced to prevent pest carryover to the subsequent season. For a closed season to be enforced, cotton plants must be destroyed to create a dead period in order to prevent build-up of pests. In countries like Zimbabwae, a closed season is governed by the Plant Pest and Disease Act, which stipulates that any farmer who fails to comply will face a fine or imprisonment or both (Mubvekeri and Nobanda, 2012). In the USA also, by the end of the 1980s, most of the cotton growers abandoned the cultivation of cotton in Arizona and California, the remaining cotton growers formed the Cotton Pest Abatement district and adopted a short season strategy and successfully managed pink bollworm on cotton (Thomas Miller, 2001). In India too, as early as 1911, cultural control in the form of removal of cotton sticks by 1 August every year was made compulsory by law to minimize incidence of pink bollworm on cotton in Madras State. Chinnababu Naik *et al*., 2018, attributed the 'Closed Season' as one of the major factors for maintaining susceptibility of PBW to *Bt* toxins in North Indian conditions. The cotton season in North India is restricted to 5-6 months to facilitate following wheat cultivation which creates a closed season, thus reduction in selection pressure because of a smaller number of PBW generations are exposed to the *Bt* toxins. However, cotton is now being cultivated over a longer season in parts of Pakistan, which might enable a higher survival rate in the bordering regions of India to elevate pestilence in north India.

Sampling and pest monitoring

Pink bollworm infestation must be closely monitored. Pheromone traps provide a reliable indication of the initial occurrence and continued infestation all through the season. Light traps also provide useful indications of pestilence. However, pheromone traps and light traps only capture moths but may or may not necessarily relate directly to the damage to squares, flowers and bolls. It is important to sample rosette flowers and green bolls regularly to assess the extent of damage and PBW population levels in the field so as to determine the best time to intervene.

Figure 6: Field monitoring and sampling

Pheromone technologies

Pheromones have been effectively used in PBW management by deploying them for monitoring, mass trapping and mating confusion. Lykouressis *et al*., 2005, evaluated the mating disruption of pink bollworm by monitoring its population with pheromone baited traps as well as sampling flowers and bolls to record damage levels in cotton fields during 1988 and 1989 in central Greece. The treated fields were compared with control fields in which 2-3 insecticide sprays were applied. In both years, the number of male moths caught in pheromone traps was greatly reduced in treated compared to control fields. Mating disruption reached 99.1%, 96.8% and 93.2% in different treated fields. In the treated fields, moth catches were reduced more in rows perpendicular rather than parallel to the prevailing wind. Staten *et al*. (1987) indicated that mating disruption greatly contributes to reducing the possibility of late outbreaks of secondary pests. Finally, it was concluded that mating disruption played a key role in reduction of pink bollworm catches in traps and lowering the damage. This effectiveness was significantly higher when planting lines were perpendicular to the direction of the prevailing winds. Damage levels were not proportionally reduced compared to the reduction of moth catches. Therefore, when mating disruption is adopted it must be accompanied by monitoring for damage levels. This clearly indicates the importance of this method in PBW management as part of Integrated Pests management (Cork and Hall, 1998). Jahnavi *et al*., 2019, reported that IPM module focusing on mass trapping of PBW resulted in less (10%) open boll locule damage due to PBW in IPM module over 24% in farmers' practice. Further, IPM module yielded 20% more seed cotton.

Conclusion

Pink bollworm is a pest that is difficult to control because it is an internal feeder and is not very vulnerable to biological control or chemical pesticides. However, it is clear from a global assessment that PBW became a major problem in countries such as India and Pakistan — countries where cotton is grown as a long season crop — whereas countries such as USA, China and Australia have either been able to eradicate it or prevent its emergence as a key problem by using a slew of IPM tactics such as short season, closed season, mating disruption and crop residue management. PBW is now a major problem in India and Pakistan. India is in a strange predicament in which 95% of its area is under hybrid cotton and the majority of cotton hybrids that are grown at low density cannot give high yields if terminated within 5-6 months; therefore neither is a short season nor a closed season possible. Pakistan is in a strange predicament because staggered sowing is followed in Sindh based on the availability of irrigation water. Staggered sowing leads to a long season that makes the crop vulnerable to PBW infestation and late season makes the crop more vulnerable to whitefly and the dreaded leaf curl virus. India and Pakistan must explore options to restrict the total area-wide cotton season within a state/province to less than six months and also to deploy strategies to retain early formed squares which enables higher yields from a short season. Other options related to fertiliser management, insecticide management, pheromone management, crop-pest asynchrony management, crop residue management, and cultural practices could lay a foundation for sustainable long term PBW management.

References

Adams, C.J., Beasley, C.A. and Henneberry, T.J., 1995. Effects of temperature and wind speed on pink boll worm (Lepidoptera: Gelechiidae) moth captures during spring emergence. *Journal of economic entomology*, *88*(5), pp.1263-1270.

Chinnababu Naik, V., Sujit, K., Sandhya Kranthi, Usha, S. and Kranthi, K. 2018. Field evolved resistance of pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) to transgenic *Bt*-cotton expressing Cry 1Ac and Cry 2Ab in India. Pest Management Science, 74(11): 1-22.

Cork, A. and Hall, D. R. 1998. Application of pheromones for crop pest management in the Indian sub-continent. *Journal of Asia-Pacific Entomology*, 35-49.

Dai, J. and Dong H. 2014. Intensive cotton farming technologies in China: achievements, challenges and countermeasures. Field Crops Res 155:99–110.

Dhurua, S. and Gujar G, T. 2011. Field-evolved resistance to *Bt* toxin Cry1Ac in the pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), from India. Pest Management Science. 67: 898-903.

Fabrick, J. A., Ponnuraj, J., Singh, A., Tanwar, R. K., Unnithan, G.C., Yelich, A. J., Li, X., Carrière, Y. and Tabashnik, B. E. 2014. Alternative splicing and highly variable cadherin transcripts associated with field-evolved resistance of pink bollworm to *Bt* cotton in India. PLoS One 9: e97900.

Frisbie, R.E., El-Zik, K.M. and Wilson, L.T., 1989. The future of cotton IPM. *Integrated Pest Management Systems and Crop Production. Wiley-Interscience. New York: John Wiley & Sons, Inc*.

Jahnavi, M., Prasad Rao, G. M.V. and Rajesh Chowdary, L. 2019. Assessment of Integrated Pest Management module for the management of Pink Bollworm in Cotton. Journal of Entomology and Zoology studies. 7 (3): 1126-1129.

Kranthi, K.R. 2012. *Bt* Cotton Q and A (Questions and Answers), 70 p.

Kranthi, K. R. 2015. Pink Bollworm strikes *Bt* cotton. (Cotton Statistics and News published by the Cotton Association of India). 2015-16, No.35 (1st December 2015), 1-5.

Kukanur, V. S., Singh, T. V. K., Kranthi, K. R. and Androw, D. A. 2018. Cry1Ac resistance allele frequency in filed populations of *Helicoverpa armigera* (Hubner) collected in Telangana and Andhra Pradesh, India. Crop Protection, 107: 34-40.

Kulakarni, Y.S. Rethrekar, V. R. and Kathavate, H. 1958. Some observations on the spotted and pink bollworms of cotton in Khandish. Indian Cotton Growers Review 12: 93-94.

Lykouressis, D., Perdikis, D., Samartzis, D., Fantinou,S. and Toutouzos,S. 2005. Management of the Pink Bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechidae) by mating disruption in cotton fields. Crop Protection, 24, 177-183.

Mathew, L. G., Ponnuraj, J., Mallappa, B., Chowdary, L.R., Zhang, J., Tay, W.T., Walsh T.K.,, Gordon, K. H. J., Heckel, D. G., Downes, S. *et al.,* 2018. ABC transporter mis-splicing associated with resistance to *Bt* toxin Cry2Ab in laboratory- and field-selected pink bollworm. Sci. Rep. 8: 13531.

Mohan, Komaralingam S. 2017. An area-wide approach to pink bollworm management on *Bt* cotton in India – a dire necessity with community participation, Current Science, Vol., 112 (10), 188-189.

Morin, S., Biggs, R.W., Sisterson, M. S., Shriver, L., Ellers-Kirk, C., Higginson, D., Holley, D., Gahan, L. J., Heckel, D. G. and Carrière, Y. *et al*., 2003. Three cadherin alleles associated with resistance to *Bacillus thuringiensis* in pink bollworm. Proc. Natl. Acad. Sci. USA 100: 5004-5009.

Mubvakeri, W. and Nobanada 2012. Cotton Research Institute and growing cotton in Zimbabwae. Department Research and specialist services, Harare.

Novo, J.P.S. and Gabriel, D., 1994. Occurrence of cotton pests in residues in gins in the region of Campinas, Sao Paulo. *Anais da Sociedade Entomológica do Brasil*, *23*(3), pp.449-453.

Singh, T. V. K., Kukanur, V.S. and Supriya, G.B. 2021. Frequency of resistance alleles to Cry1Ac toxin from cotton bollworm, *Helicoverpa armigera* (Hübner) collected from Bt-cotton growing areas of Telangana state of India. Journal Invertebrate Pathology. Available online 19 February 2021, 107559.

Staten, R. T., Flint, H. M., Weddle, R. C., Quintera, E., Zarate, R.E., Finnel. C. M., Hernade, M. and Yamamoto, A.1987. Pink bollworm (Lepidoptera: Gelichidae), large scale field trials with a high rate gossyplure formulation. *Journal Economic Entomology*, 80:1267-1271.

Tabashnik, B. E. and Carrier, Y. 2019. Global Patterns of Resistance to *Bt* Crops Highlighting Pink Bollworm in the United States, China, and India, Journal of Economic Entomology, XX(XX), 1-11.

Thomas Miller, 2001. Control of pink bollworm, Pesticide Outlook-April 2001, P 68-70.

Wan, P., D. Xu, S. Cong, Y. Jiang, Y. Huang, J. Wang, H. Wu, L. Wang, K. Wu, Y. Carrière, et al. 2017. Hybridizing transgenic *Bt* cotton with non-*Bt* cotton counters resistance in pink bollworm. Proc. Natl. Acad. Sci. USA 114: 5413–5418.

Wang, L., J. Wang, Y. Ma, P. Wan, K. Liu, S. Cong, Y. Xiao, D. Xu, K. Wu, J. A. Fabrick, *et al.,* 2019. Transposon insertion causes cadherin missplicing and confers resistance to *Bt* cotton in pink bollworm from China. Sci. Rep. 9: 7479.

Wang, R.H., Guo, X.M. and Li, G.Y., 1993. Breeding studies on upland cotton germplasm Zhong 99 resistance to insects (*Aphis gossypii* and *Pectinophora gossypiella*) and diseases (*Fusarium vasinfectum* and *Verticillium dahliae* Kleb.). *Scientia Agricultura Sinica*, *26*(5), pp.32-37.

Wu, Z.B., 1993. The selection of and research on the new insect resistant cotton variety Huamian 101. *China Cottons*, *20*(2), pp.18-19.