



T. P. Rajendran, Ajanta Birah, and Prasad S. Burange

Contents

11.1	Introduction.....	361
11.2	Pests	366
11.2.1	Sap-Sucking Pests.....	366
11.2.2	Insect Pests Damaging Fruiting Bodies	375
11.2.3	Other Foliar and Minor Pests.....	385
11.3	Integrated Pest Management in Cotton Crop.....	396
11.4	Conclusion	405
	References.....	406

11.1 Introduction

Cotton, the king of natural fibres since antiquities, has been entwined in human civilization (Smith and Cothren 1999; Sethi 1960). It is the most popularly used fibre for clothing and for a host of other purposes since Vedic times in India. The earliest global historical records show them as shrouds of woven cotton fabric in Egyptian mummies of 5000 BC. Ripe cotton bolls (capsule) that dehisce after drying of their rind expose the seed cotton. The tubular outgrowth of seed coat cells gets cellulosic deposit during maturation of bolls. Once the fibre dries up after boll opening, the lumen collapses and the fibre takes the shape of a ribbon (Munro 1994).

T. P. Rajendran (✉)

Research Information System for Developing Countries (RIS),
Lodhi Road, New Delhi 110003, Delhi, India

A. Birah

ICAR-National Research Centre for Integrated Pest Management,
IARI Campus, New Delhi 110012, Delhi, India

P. S. Burange

Department of Entomology, Punjab Agricultural University, Ludhiana 141004, Punjab, India

Cotton crop yields lint that serves the country's industrial raw material requirement. The crop and its industrial commodity demand large labour force in the country. The crop occupies approximately 5–8% of the total cultivable area in the country. The area enhancement in the last 10 years due to wide adoption of genetically modified cotton hybrids expressing insecticide protein, Bt delta-endotoxin, could reduce bollworm damage and enhance seed cotton yield. Cotton cropping encompasses diversity in terms of vastness, agroclimate, farming methods, cropping systems, planting and market seasons, varieties, duration, quality, costs and returns. Rural economy in dryland regions of the country is influenced by this crop commodity. Cotton contributes to employment sustenance of approximately 200 man days/ha for cultivation alone; in processing, in marketing and in various industries, it is further contributing annually.

Gossypium spp. are botanically fibre-yielding plants from seeds. Diploid species ($2n = 26$) such as *G. arboreum* L. and *G. herbaceum* L. are indigenous to Asia and Africa, popularly known in India as *desi* cotton. The New World cottons are tetraploid species ($2n = 52$) such as American origin *G. hirsutum* L. and the Egyptian *G. barbadense* L. These were introduced into our country during the seventeenth to eighteenth centuries and became popular for cultivation in India, while in the rest of the world, any one or two species are cultivable. Cotton varieties under each species with specific fibre property traits and agronomy could be grown in northern states of Punjab, Haryana and Rajasthan; central zone states of Maharashtra, Gujarat, Madhya Pradesh and Odisha; and south zone states of Andhra Pradesh, Telengana, Karnataka and Tamil Nadu (Santhanam and Sundaram 1999).

Cotton plant is reported to host about 1326 species of insects (Hargreaves 1948). Among these, most insects are casual visitors and are not observed to feed on cotton tissues. In India too, there are over 166 insects recorded as pests on cotton crop (Ayyar 1932; Khan and Rao 1960; Ingram 1981; Puri et al. 1999). They are categorized as sucking insects, boll feeders and foliar and stem feeders (Table 11.1). A spectrum of these insects in different crop phenological stages and geographical areas denote their adaptability to the habitat of such agroclimatic conditions. In India, cotton crop is damaged right from seedling stage by a number of pests, such as grasshoppers, viz. *Chrotogonus* sp., *Atractomorpha crenulata* (Fabricius), *Acrida exaltata* Walker and *Oxya velox* (Fabricius); crickets, viz. *Brachytrupes portentousus* (Lichtenstein & A.A.H.), *Gryllus viator* Kirby, *Gryllus domesticus* (Linnaeus) and *Poeciloceris pictus* (Fabricius); cutworms, viz. *Agrotis* spp., *Euxoa segetum* Denis & Schiffermüller and *E. spinifera* (Hübner); leaf worm, *Spodoptera exigua* (Hübner); weevils, viz. *Atactogaster finitimus* (Fabricius) and *Mylocheris* spp.; red spider mites; etc. (Anonymous 2010). However, the plant recovers from the damage, and hence there is no serious impact on the crop. These pests are managed due to the early-season application of pesticides (including pesticide seed treatment) and natural enemies (Table 11.2) in the crop. Polyphagous pests on cotton crop across Indian cotton-growing states, causing serious economic crop damage, are sap-sucking ones, such as aphids, jassids, mealybugs, whiteflies, thrips, mites and a number of caterpillar pests, such as bollworms, *Spodoptera* spp., *Anomis* spp. and leaf folders, red cotton bug (cotton stainer bug) such as *Dysdercus* spp. and dusky cotton bug such as *Oxycarenus hyalinipennis* (Costa) and *O. laetus* Kirby. The plant sap feeders, foliar

Table 11.1 List of cotton pests in India

Name of the pest	Scientific name	Family	Order
(a) Borers			
American bollworm	<i>Helicoverpa armigera</i> (Hübner)	Noctuidae	Lepidoptera
Pink bollworm	<i>Pectinophora gossypiella</i> (Saunders)	Gelechiidae	Lepidoptera
Spiny bollworm	<i>Earias insulana</i> (Boisduval)	Nolidae	Lepidoptera
Spotted bollworm	<i>Earias vittella</i> (Fabricius)	Nolidae	Lepidoptera
Stem weevil	<i>Pempherulus affinis</i> (Faust)	Curculionidae	Coleoptera
Shoot weevil	<i>Alcidodes affaber</i> Aurivillius	Curculionidae	Coleoptera
(b) Foliage feeders			
Leaf worm	<i>Spodoptera litura</i> (Boisduval)	Noctuidae	Lepidoptera
Leaf roller	<i>Syllepte derogata</i> (Fabricius)	Pyraustidae	Lepidoptera
Semiloopers	<i>Anomis flava</i> (Fabricius)	Noctuidae	Lepidoptera
	<i>Acontia graellsii</i> (Feisthamel)	Noctuidae	Lepidoptera
	<i>Tarache opalinoides</i> Guenée	Noctuidae	Lepidoptera
	<i>Tarache basifera</i> Walker	Noctuidae	Lepidoptera
Leaf perforator	<i>Bucculatrix loxoptila</i> Meyrick	Bucculatricidae	Lepidoptera
Ash weevils	<i>Mylocherus maculosus</i> (Desbrochers)	Curculionidae	Coleoptera
	<i>Mylocherus subfasciatus</i> Guerin	Curculionidae	Coleoptera
	<i>Mylocherus viridanus</i> Fabricius	Curculionidae	Coleoptera
	<i>Mylocherus discolor</i> Boheman	Curculionidae	Coleoptera
Surface weevil	<i>Attactogaster finitimus</i> Faust	Curculionidae	Coleoptera
Hairy caterpillars	<i>Euproctis fraterna</i> Moore	Lymantriidae	Lepidoptera
	<i>Pericallia ricini</i> Fabricius	Arctiidae	Lepidoptera
	<i>Estigmene lactinea</i> (Cramer)	Arctiidae	Lepidoptera
Red hairy caterpillars	<i>Amsacta albistriga</i> Walker	Arctiidae	Lepidoptera
Cotton grasshopper	<i>Cyrtacanthacris tatarica</i> (Linnaeus)	Acrididae	Lepidoptera
Tobacco grasshopper	<i>Atractomorpha crenulata</i> (Fabricius)	Pyrgomorphidae	Lepidoptera
(c) Flower feeders			
Blister beetle	<i>Mylabris pustulata</i> (Thunberg)	Meloidae	Coleoptera
Flower weevil	<i>Amorphaidea arcuata</i> Motschulsky	Curculionidae	Coleoptera
(d) Sap feeders			
Leafhopper	<i>Amrasca biguttula biguttula</i> Ishida (syn. <i>Empoasca</i> Walsh/ <i>Amrasca devastans</i> Distant)	Cicadellidae	Hemiptera
Aphid	<i>Aphis gossypii</i> Glover	Aphididae	Hemiptera
Whitefly	<i>Bemisia tabaci</i> (Gennadius)	Aleyrodidae	Hemiptera
Cotton mealybug	<i>Phenacoccus solenopsis</i> Tinsley	Hemiptera	Pseudococcidae

(continued)

Table 11.1 (continued)

Name of the pest	Scientific name	Family	Order
Papaya mealybug	<i>Paracoccus marginatus</i> Williams and Granara de Willink	Hemiptera	Pseudococcidae
Thrips	<i>Thrips tabaci</i> Lindeman	Thripidae	Thysanoptera
	<i>Thrips palmi</i> Karny	Thripidae	Thysanoptera
	<i>Scirtothrips dorsalis</i> Hood	Thripidae	Thysanoptera
Red cotton bug	<i>Dysdercus cingulatus</i> (Fabricius)	Pyrrhocoridae	Hemiptera
	<i>Dysdercus koenigii</i> (Fabricius)		
	<i>Dysdercus similis</i> Freeman		
Dusky cotton bug	<i>Oxycarenus hyalinipennis</i> (Costa)	Lygaeidae	Hemiptera
	<i>Oxycarenus laetus</i> Kirby		

Table 11.2 Natural enemies of in cotton agroecology

S. no.	Parasitoids	Pest
1	<i>Aphelinus</i> sp.	Spotted bollworm
2	<i>Erythmelus empoasca</i> Subba Rao	Spotted bollworm
3	<i>Gonatocerus</i> sp.	Spotted bollworm
4	<i>Trichogramma achaeae</i> Nagaraja and Nagarkatti	Pink bollworm
		Spotted bollworm
5	<i>Trichogramma brasiliensis</i> (Ashmead)	Spotted bollworm
6	<i>Trichogramma chilonis</i> Ishii	Spotted bollworm
		American bollworm
7	<i>Trichogramma chilotraeae</i> (Nagaraja and Nagarkatti)	Spotted bollworm
		Pink bollworm
8	<i>Telenomus remus</i> Nixon	Spotted bollworm
9	<i>Trichogrammatoidea</i> sp. near <i>guamensis</i> Nagaraja	Pink bollworm
		Spotted bollworm
10	<i>Agathis fabiae</i> (Nixon)	Spotted bollworm
		Pink bollworm
11	<i>Apanteles angaleti</i> Muesebeck	Pink bollworm
12	<i>Bracon chinensis</i> Fahringer	Pink bollworm
13	<i>Bracon greeni</i> Ashmead	Pink bollworm
		Spotted bollworm
14	<i>Bracon kirkpatricki</i> (Wilkinson)	Spotted bollworm
15	<i>Bracon brevicornis</i> (Wesmael)	Spotted bollworm
16	<i>Bracon hebetor</i> Say	Spotted bollworm
17	<i>Camptolilthipsis gossypiella</i>	Pink bollworm
18	<i>Rogas aligarhensis</i> Quadri	Pink bollworm
		Spotted bollworm
19	<i>Goniozus</i> sp.	Pink bollworm
20	<i>Campoletis chlorideae</i> Uchida	American bollworm
21	<i>Elasmus johnstoni</i> Ferrière	Pink bollworm
22	<i>Eriborus argenteopilosus</i> (Cameron)	Semilooper
		American bollworm
23	<i>Pyemotes ventricosus</i> (Newport)	Pink bollworm

(continued)

Table 11.2 (continued)

24	<i>Chelonus</i> sp.	Bollworms
25	<i>Chelonus blackburni</i> Cameron	Pink bollworm
26	<i>Microchelonus Chelonus versatilis</i> (Wilkinson)	American bollworm
27	<i>Xanthopimpla punctata</i> (Fabricius)	Cotton leaf roller
28	<i>Brachymeria euploaeae</i> (Westwood)	Cotton leaf roller
29	<i>Apanteles</i> sp.	Spotted bollworm
30	<i>Brachymeria nephantidis</i> Gahan	Spotted bollworm
31	<i>Encarsia formosa</i> Gahan	Whitefly
32	<i>Encarsia shafeei</i> Hayat	Whitefly
33	<i>Eretmocerus mundus</i> Hayat	Whitefly
34	<i>Aphilinus</i> sp.	Aphids
	Predators	Pest
1	<i>Chrysoperla carnea</i> Stephens	Sucking pests bollworms
2	<i>Brumus suturalis</i> (Fabricius)	Sucking pests and bollworms
3	<i>Coccinella septempunctata</i> (Linnaeus)	Sucking pests and bollworms
4	<i>Menochilus sexmaculatus</i> (Fabricius)	Sucking pests and bollworms
5	<i>Geocoris ochropterus</i> (Kapadia and Puri)	Pink bollworm and jassid
6	<i>Geocoris</i> sp.	Sucking pests
7	<i>Zelus</i> sp.	Sucking pests
8	Spiders	Sucking pests and adult bollworms
9	<i>Eocanthecona furcellata</i> (Wolff)	Bollworms
10	<i>Encarsia</i> sp.	Whitefly
11	<i>Syrphus confracter</i> (Wolff)	Aphids
12	<i>S. balteatus</i> (De Geer)	Aphids
13	<i>S. searius</i> Weidman	Aphids
14	<i>Chrysoperla carnea</i> (Stephens)	Aphids, jassids
15	<i>Cheilomenes sexmaculata</i> (Fabricius)	Aphids
16	<i>Ectomocoris tibialis</i> Distant	<i>Dysdercus cingulatus</i> (Fabricius)
17	<i>Rhynocoris fuscipes</i> (Fabricius)	<i>Spodoptera litura</i> (Fabricius)
		<i>Achaea janata</i> (Linnaeus)
		<i>Dysdercus cingulatus</i> (Fabricius)
		<i>Mylabris indica</i> (Thunberg)
18	<i>Rhynocoris kumarii</i> Ambrose and Livingstone	<i>Helicoverpa armigera</i> (Hübner)
		<i>Anomis flava</i> (Fabricius)
19	<i>Rhynocoris longifrons</i> Stål	<i>Spodoptera litura</i> (Fabricius)
		<i>Helicoverpa armigera</i> (Hübner)
		<i>Dysdercus cingulatus</i> (Fabricius)
S.no.	Insect pathogens	Pest
1	<i>Aspergillus</i> sp.	Caterpillar pests
2	<i>Beauveria bassiana</i> (Bals.-Criv.) Vuill.	Caterpillar pests
3	<i>Nomuraea rileyi</i> (Farlow) Samson	Caterpillar pests
4	<i>Metarhizium anisopliae</i> (Metchnikoff) Sorokin	Caterpillar pests
5	<i>Bacillus thuringiensis</i> Berliner	Caterpillar pests
6	<i>Bacillus subtilis</i> (Ehrenberg) Cohn	American bollworm
7	Nuclear polyhedrosis virus	American bollworm
8	<i>Cytoplasmic polyhedrosis virus</i>	American bollworm

and flower feeders and fruit and stem borers dominate the cultivators' fields during every crop season. Depending upon the susceptibility of the crop genotype, farmers have to use various insecticides to protect the crop from depredation of these pests. The spectrum of pests in cotton crop is given in Table 11.1.

11.2 Pests

11.2.1 Sap-Sucking Pests

These insects are specialized with piercing and sucking mouthparts. They inject saliva into the tissues and suck back the phloem substance. The undigested, excess plant sap is excreted, often called as 'honeydew' due to it containing sugars, and hence it is sweet. The excess honeydew secretion due to luxury consumption could encourage growth of black sooty mould, disrupting photosynthesis of leaves.

11.2.1.1 Jassids, *Amrasca biguttula biguttula* Ishida (Hemiptera: Cicadellidae) (Syn. *Empoasca* Walsh/*Amrasca devastans* (Distant))

Description

Adults have prominent black spots on both sides of the median line in the vertex of the head and another on the apical area of the forewing. The nymphs walked diagonally, face usually pale greenish, tegmina shining and wings hyaline iridescent. Forewings were yellowish green in colour. The length of male hoppers varied from 2.50 to 2.60 mm. In the case of female hopper, the length varied from 2.68 to 2.76 mm, while breadth varied from 0.73 to 0.77 mm.

These are leafhoppers that invade cotton plants from around the time of germination of the crop. These are polyphagous pests that invade during *kharif* season many crops and those naturally growing plants in the uncultivated area too. Jassids are greenish-coloured insects whose adults measure 2–3 mm. The young ones called nymphs are without wings and live on the same tissues of the crop. The adults move around on crop tissues, while nymphs restrict themselves under leaves. Leafhoppers are agile insects that move with equal ease either forwards, backwards or sideways like a crab. They fly around in the crop. They become part of the aerial plankton, being wafted in the surface air movements.

Symptoms of Infestation and Damage

The invasion of hoppers on cotton causes brown blotches/spots on leaf surface that cup upwards. Under heavy damage, the 'hopper-burn' symptoms due to coalesced brown spots make the crop look very ugly with a burnt look. Many patchy hopper burns indicate the severity of damage in the cotton fields. The farms look diseased when the jassid damage is severe, especially in highly susceptible cotton varieties. Many modern transgenic cotton hybrids with genetic modification for bollworm tolerance using delta-endotoxin expressing genes are noticed to be susceptible to jassid damage. Often, when the cotton crop is prone to early-season pests such as

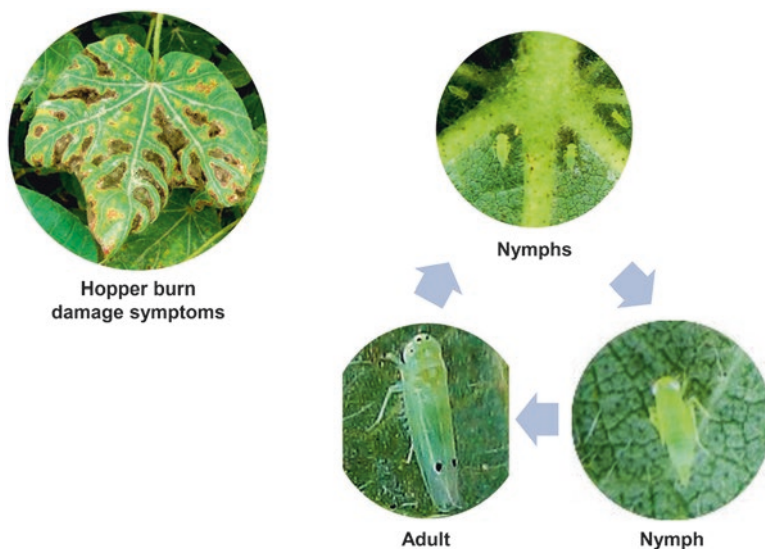


Plate 11.1 Life cycle of cotton jassid (leafhoppers), *Amrasca biguttula biguttula* (Ishida)

jassids, the vigour of the crop is put to challenge, and its growth and metabolism are not attained to the desired level.

Their damage emanates from their intense feeding habit on the leaf lamina. They puncture the epidermis and veins by inserting needle-like proboscis and injecting the saliva that creates a tube through which they suck the cell content. Being phloem feeders, they suck in the plant sap containing lots of sugars. The nutritional requirement of hoppers for protein available in the plant sap is utilized, and the balance excess fluid is excreted as 'honeydew'. The honeydew spread on leaf lamina encourages sooty mould growth and makes the leaves black in colour, preventing photosynthesis.

Biology

The *Amrasca* hoppers in cotton lay eggs on the midrib vein of leaves. The eggs hatch and the young nymphs feed on the lower side of leaves. The eggs can remain dormant under inclement weather conditions. During season, each female lays on an average 20–25 eggs. The total nymph period is about 10–15 days according to varying growing day degrees of the season in cotton crop (Plate 11.1). The males live for about 16 days, while the female hoppers live for 17–18 days according to the condition of host plant and growing day degree. The hoppers are known to fly short distances, while they are generally wafted in surface wind currents and carried to long distances. These species of jassids have wide host range, and they can flourish their population unchallenged throughout the entire crop growing season. While their few natural enemies (Table 11.1) do keep their outbreak under check normally (Anonymous 2010), the outbreak populations of jassid in cotton under the influence of higher soluble nitrogen in the growing tissues, supported by high humidity due to rains and irrigations, create huge pestilence in the cotton crop across the country.

11.2.1.2 Aphids, *Aphis gossypii* Glover (Hemiptera: Aphididae)

Description

Yellowish green to dark olive green, orange-yellow colour for adult apterous females and black soft-bodied sap-sucking pest is polyphagous and cosmopolitan species with distribution in all regions of the world except the Arctic region. The aphid colonies bear individuals having varying colours (Plate 11.2). The pest is seen in cotton within 20 days after crop establishment after cotton germination of every season. They live on a number of alternate hosts as also on vegetable crops throughout the year. The apterae have six segmented antennae; tibiae are pale and darker brown at extremity. Tarsi are dark. Cornicles are black and twice as long as the paler cauda, which have five to seven hairs. The alatae have dusky head and thorax; cornicles are black and 1.5 times to twice as long as the smoky ochraceous cauda. Antennae are two-thirds to three-quarters of body length with terminal process 2.5–3 times as long as its base. This aphid species is seen to show morphological variability to throw challenge at entomologists for their identity.

Symptoms of Infestation and Damage

Tender leaves crinkle due to heavy aphid infestation. Yellowing of leaves, stunted growth and honeydew secretion causing stickiness of cotton lint are the major symptoms of *A. gossypii* infestation.

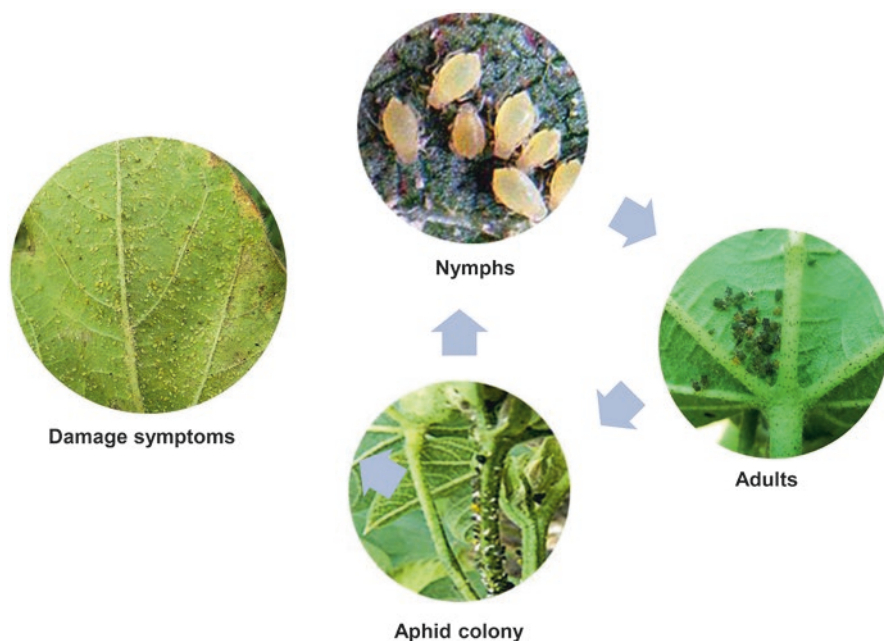


Plate 11.2 Life cycle of aphid, *Aphis gossypii* Glover

Biology

The aphids are soft-bodied animals that have sexual dimorphism. Based on fecundity of this aphid on various hosts, it is reported (Leclant and Deguine 1994) that various hosts provide differential nutrition that guides its fecundity on them. Several biotypes are described based on the adaptation to weather conditions and hosts (Eastop and Hill Ris Lambers 1976). These aphids live underside of leaves, tender stems and growing tip of cotton plants and suck the phloem sap. Myrmecophily is well known for this aphid species, and a number of ant species serve them in attendance for movement of young nymphs between plants as well as for certain protection from some natural enemies. The ants feed on the honeydew that has sugars in addition to proteins and minerals. Trapping with yellow sticky traps during the beginning of cotton season would provide the onset of aphid infestation by looking at the alate adult aphid population in the aerial plankton that is wafted in air currents. The rainfed areas under cotton in India and West and Central African countries follow similar pattern of appearance in cotton immediately after germination. They tend to quickly generate two to four generations before the monsoon rains become severe (Plate 11.2). The rains wash away much of the aphids. During early stage of the crop, the hairy types of varieties may have severity of damage and their leaf lamina cup upwards. However, they are seen to further flourish in the crop during mid-growing season onwards. In many situations, the honey exuded makes the cotton fibre to stick together interfering in the ginning process, causing loss of the commodity. The farmers endure lower price in market for sticky cotton.

11.2.1.3 Whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae)

Description

Whitefly infestation in cotton commences from the seedling stage and peaks up in the grand-growth stage (Husain and Trehan 1933). This whitefly species is known to be reported on 315 host plants worldwide (Mound and Halsey 1978). These flourish under dry and warm weather conditions. Higher nitrogen index of the crop spikes their population. The immature larvae, puparia and adults are seen in abundance when the outbreak is severe. Generations overlap (Reddy and Rao 1989). Honeydew produced by these fall on leaves and open boll lint. The sticky cotton due to the honeydew is a serious problem in fibre-processing sector. This cotton pest is well known to be the vector of cotton leaf curl virus (CLCuV) disease (Plate 11.3). Another whitefly species reported on cotton is spiralling whitefly, *Aleurodicus dispersus* Russell.

Biology

Microclimatic conditions are one of the strong determinants on the buildup of this pest. Closed canopy and close spacing encourage high breeding of the insect (Osgur and Sekeroglyu 1984). Pesticide treatment has been for long the recourse for whitefly outbreak. However, it is advisable to regulate the nitrogen fertilizer dose in the early phase of crop growth so as to reduce outbreak populations of whitefly. Leaf chemical characteristic, such as leaf pH, has been indicated to be perceived by this

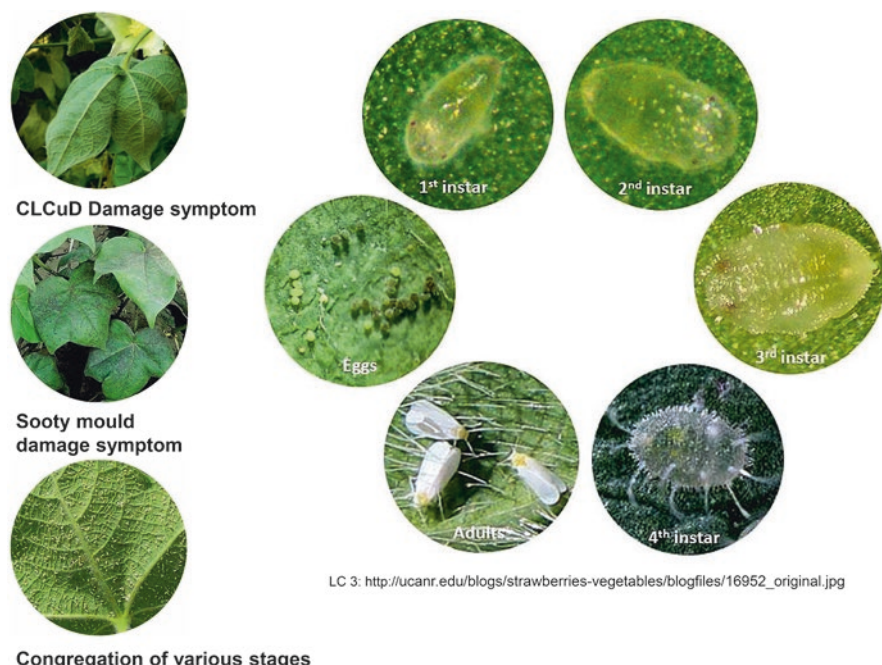


Plate 11.3 Life cycle of whitefly, *Bemisia tabaci* (Gennadius)

insect for feeding preference (Berlinger et al. 1983). Leaf content pH manipulation, leaf glabrosity, okra leaf shape, open canopy and low leaf hair density offer varying degrees of whitefly tolerance in cotton crop (Avidov 1956). This pest insect has been kept under control under normal agronomic practices using spraying of methyl demeton 25 EC at 2 l/ha, neem oil + teepol (3 ml + 1 ml/1 water), imidacloprid 70 WG 750 ml/ha and phosalone 35 EC at 2 l/ha.

11.2.1.4 Mealybugs (Hemiptera: Pseudococcidae)

Description

Four mealybug species, viz. the solenopsis mealybug, *Phenacoccus solenopsis* Tinsley; the pink hibiscus mealybug (Plate 11.4), *Maconellicoccus hirsutus* (Green); the papaya mealybug, *Paracoccus marginatus* Williams and Granara de Willink; and the spherical mealybug, *Nipaecoccus viridis* Newstead, were found to infest cotton plants in India.

Phenacoccus solenopsis Tinsley (Hemiptera: Pseudococcidae)

During 2007, *P. solenopsis* was found to be the predominant mealybug species, comprising 95% of the samples examined from 47 locations representing cotton-growing states of India (Dhara Jothi et al. 2008; Jhala et al. 2008; Nagrare et al.

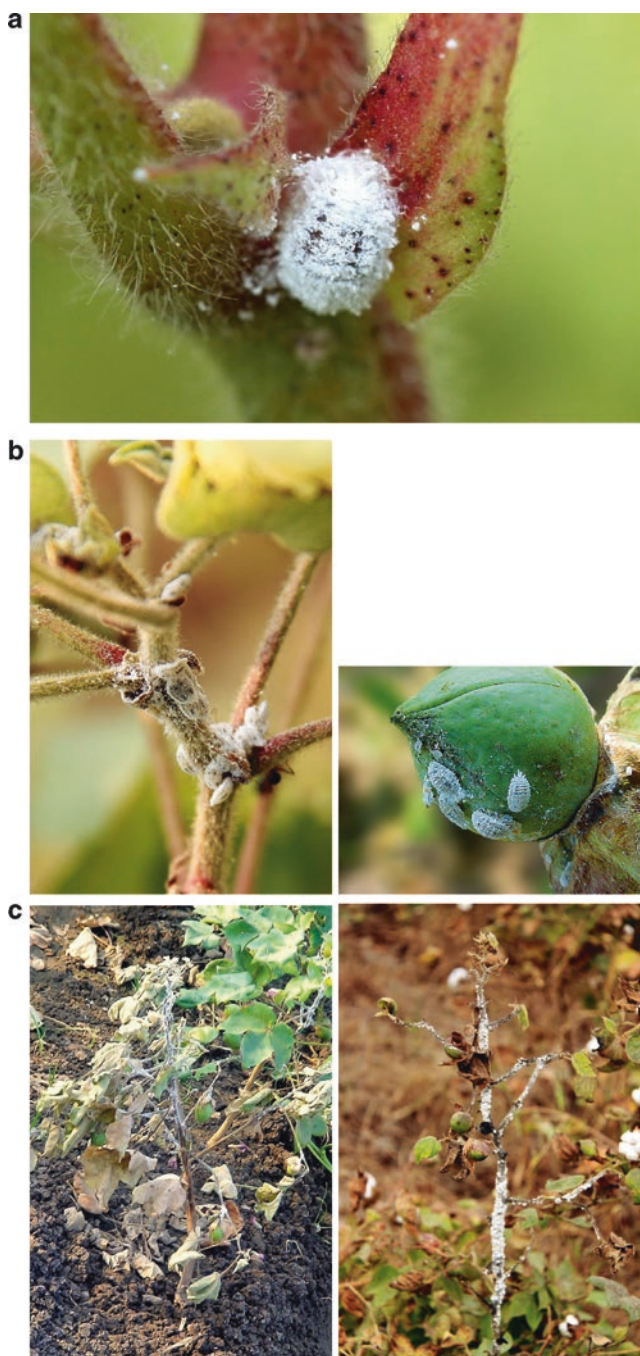


Plate 11.4 (a) Female *Phenacoccus solenopsis* Tinsley (b) *Phenacoccus solenopsis* Tinsley infestation (c) Damage symptoms of *Phenacoccus solenopsis* Tinsley infestation

2009; Monga et al. 2009; Vennila et al. 2010; CABI 2015). Tinsley (1898) described the *Phenacoccus solenopsis* from Mexico. Synonyms of *P. solenopsis*, *P. gossypiphilous* Abbas, *P. solani* Ferris, *P. defectus* Ferris, *P. gossypii* Townsend & Cockerell, *P. solenopsis* Tinsley and *Paracoccus marginatus* Williams and Granara de Willink, are declared exotic pests and proved to be invasive to various host plants including crops such as cotton (Plate 11.4). Widespread invasion in the length and breadth of India of these two species significantly challenged farmers, albeit the fact that these pests were efficiently managed with agroecological solutions. Neighbouring countries, such as Pakistan (Abbas et al. 2005) and Sri Lanka (Prishanthini and Laxmi 2009), suffered the invasion of *P. solenopsis* and consequent economic loss to cotton and many flora.

This species of mealybug is a significant invasive pest that India had to bear the brunt within various plants, particularly of Malvaceae family. Cotton became its victim, especially in southern India where this pest erupted for the first time and spread to central Indian cotton-growing states. Its severe infestation caused drying of fruiting bodies on the crop created, and the panicked farmers went about insecticide sprays that became counterproductive to suppress the pest in the crop.

Pink Hibiscus Mealybug, *Maconellicoccus hirsutus* (Green)

This horticultural crop pest moved into cotton crop too during the last decade of this century. The pest became menacing in southern and northern Indian states, challenging farmers for quick suppression in the early crop growing stage.

Occurrence of *M. hirsutus* on cotton still remains rare and sporadic like it had always been in India and thus deserves least attention. *P. solenopsis* was hitherto not reported to occur in India, observed to be widespread on cotton in almost all cotton-growing states of the country. It is considered to be an exotic species that has its origin in the USA. *P. marginatus* also infests cotton and was found to be a sporadic cum potential pest in south zone.

The occurrence of the scale insect, *Nipaecoccus viridis* Newstead, was found to be sketchy and less frequent on cotton or any other plants including weeds. In cotton agroecosystem, four more species, viz. *Coccidohystrix insolita* Green, *Ferrisia virgata* Cockrell, *Drosicha mangiferae* Green and *Ferrisia malvastra* (McDaniel), on pigeon pea, guava, mango and a weed host *Sonchus oleraceus* L. were also observed although rare in occurrence. Besides all four species of cotton, *P. solenopsis* was found to infest other cultivated crops like okra, tomato, chilli, brinjal, potato, cluster bean, green gram, papaya and sunflower. A record of 166 host plants of *P. solenopsis* belonging to 51 families comprising 78 weeds, 27 ornamentals, 19 trees, 17 vegetables, 12 field crops, eight fruit plants and five spice plants was made in three cotton agroecosystems of India. A great biodiversity of natural enemies of mealybugs have been recorded, which are helping in keeping population of mealybug under check. Among them, *Aenasius bambawalei* Hayat is observed to be a potential parasitoid. Its presence was seen all over the country.

11.2.1.5 Green Bugs (Hemiptera: Miridae)

In recent times, mirid bugs have become significant in damaging cotton fruiting bodies (Manohar et al. 2012; Udikeri et al. 2010a, b). Three species of mirid bugs occur in India among which *Campylomma livida* (Reuter) (Plate 11.5a) and *Hyalopepsus lineifer* (Walker) are the dominant species in north and central India, while *Poppiocapsidea* (syn. *Creontiades*) *biseratense* (Distant) (NBAIR 2016) (Plate 11.5b) is dominant in south India. Preferential egg laying on leaf petiole egg cap projects above petiole surface. In Australia, these bugs became major pests with the introduction of transgenic Bt cotton in 2000 (Khan et al. 2004). While feeding on terminal shoots, fruiting forms, young leaves, etc., they inject pectinase enzyme and other chemicals in saliva that cause tissue damage and discolouration at feeding sites. Parrotbeaking of bolls is routinely observed as damage due to the feeding. The seed numbers and lint development in these bolls are poor. In central and southern India, another species, *Helopeltis antonii* Signoret, is seen to damage cotton plants feeding on stem, foliage, buds and bolls.

Biology

C. livida and *P. biseratense* are swift fliers, nymphs small with yellowish abdomen. They move fast when disturbed. *H. lineifer* is a brownish bug.

Eggs are cylindrical, slightly recurved and laterally compressed, shining white in colour, turning to yellow as it matures. Eggs hatch within 4–5 days. There are five nymphal instars, each of about 2–3 days' duration. The wing pads start to develop at the third instar. Adults are elongated, about 7–9 mm long, with long legs and antennae. Development from egg to adult takes about 15–18 days. The adults can live for 3–5 weeks, and a female can lay up to 80 eggs in the lifetime.

Oval egg cap protrudes on leaf petioles. Eggs hatch out in 3–4 days. There are five nymphal instars of 2–3 days' interval depending on the temperature ranging between 30 and 32°C. Preferential egg laying on leaf petioles with the egg cap projecting out of the petiole surface is common. The nymphs vary in size between 1.5 and 6.7 mm. The summer generation time is three weeks. Adult longevity is 3–4 weeks and actively feed on the fruiting parts of cotton plant.

The economic threshold level (ETL) during cooling period is 0.15 mirid bug/m whereas 1.5 mirid/m row by beat sheet method. During cool period the pest multiplication rate is high. The population declines beyond 35°C. Heavy rains bring down their population. During warm season the ETL is 0.1 mirid/m row. Alternate host crops are lucerne, pigeon pea, sunflower, safflower, sorghum, maize, pearl millet, *Sesbania aculeata* (Jacq.) W. Wight, castor, amaranthus, Indian mallow, pigweed, turnip weed, soybean, mung bean, groundnut, etc.

Damage

Both nymph and adult stages cause damage. Feeding on the terminal growth, squares, flowers and bolls of cotton plants with the piercing/sucking mouthparts, excessive shedding of flowers, small squares and immature bolls happen in the cotton crop. The feeding results in small, dark, sunken lesions on the surface of the boll, and in severe cases, deformed bolls are formed due to lack of fertilization

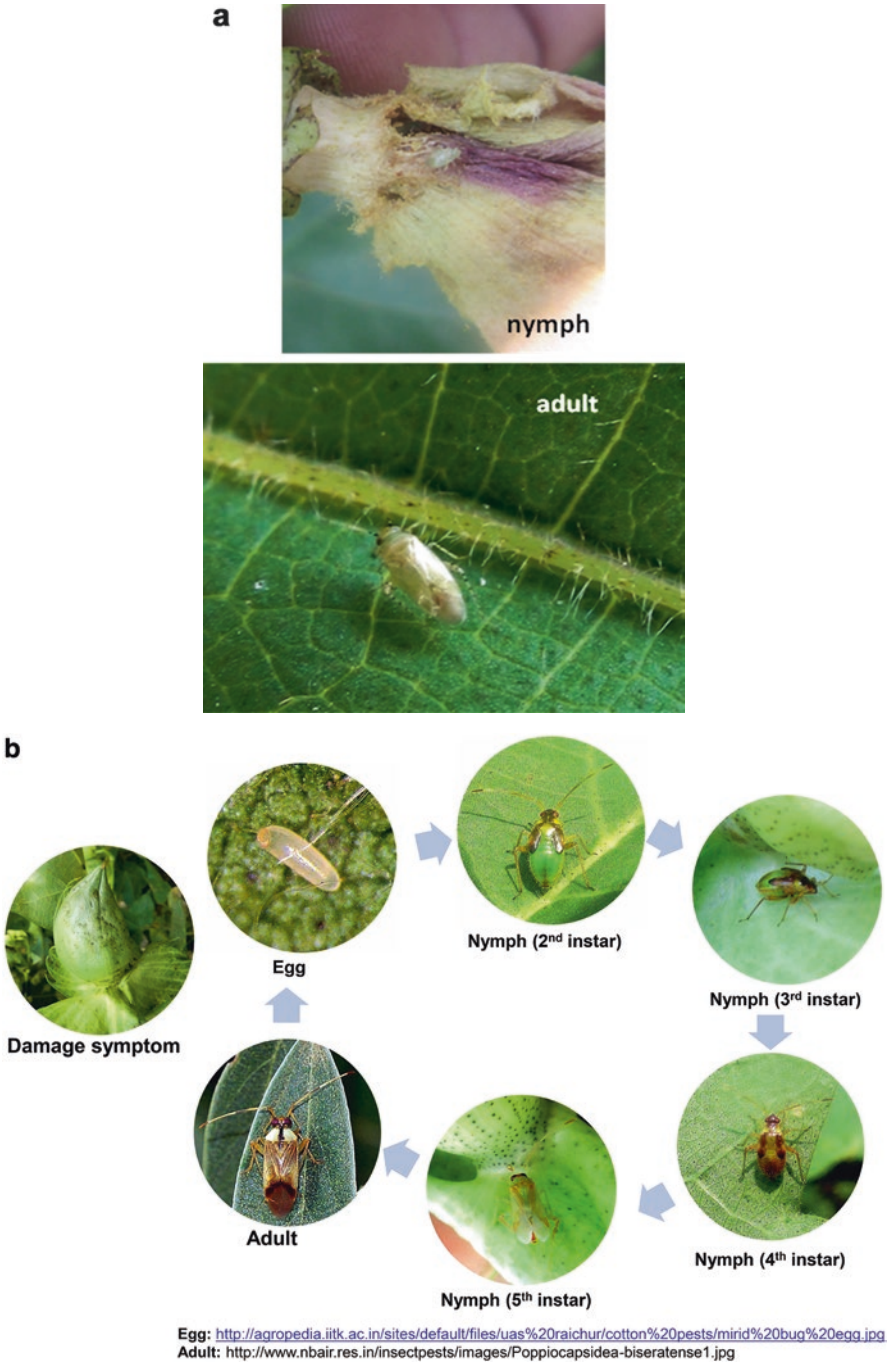


Plate 11.5 (a) Mirid bug, *Campylomma livida* (Reuter). (b) Life cycle of mirid bug, *Poppiocapsidea biseratense* (Distant)

of some ovules. This symptom is often referred to as ‘parrotbeaking’ of bolls. The female mirid lays egg singly, preferentially on the leaf petiole. They suck plant sap from growing terminals, young leaves, squares, small bolls, etc. The ‘parrot-beak’ of damaged bolls is characteristic due to their intensity of feeding. Release of pectinases, other enzymes and other chemical ingredients in their saliva causes tissue damage at feeding site; the zone finally blackens and dies. The fruiting bodies turn yellow and are dropped off. The lint quality of parrot-beaked bolls is found to be poor.

11.2.1.6 Thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae)

Description

Yellowish, soft-bodied elongated insects measuring 1.0–2.5 mm length that have imperfect wings with fringes of cilia (*thysano* = fringe). The adults have two eyes and three ocelli on head in a triangular layout on head, the two antennae with seven segments on each. There are three stylets: one on left mandible, the right mandible being atrophied; the two maxillary lacinia, U-shaped in cross section, and connected directly to pharyngeal and saliva pumps in the hypopharynx. Maxillary palps with several segments and two labial palps on labium are characteristics of thrips. Ten-segmented abdomen is long and bears ovipositor in females (Bournier 1994). Macropterous adults are pale yellow to brown in colour (Plate 11.6).

Symptoms of Infestation and Damage

With rasping mouthparts, the damage done by thrips are easily identified with an oily sheen, after the chlorophyll is rasped out intensely, making the leaf lamina to cup upwards (Attique and Ahmad 1990; Bournier 1994)

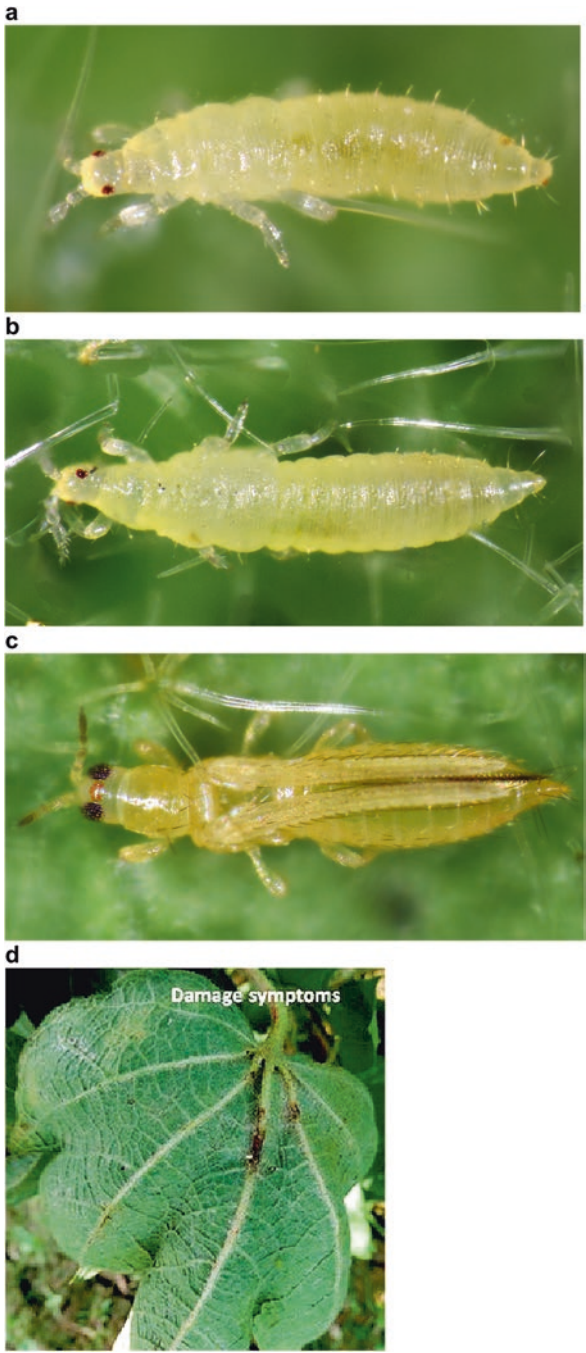
Biology

The eggs are long and reniform; two to five of them are laid per day on the underside of leaf lamina into the epidermis of the leaf lamina and veins. Under cooler weather conditions, the egg period prolongs even for three weeks. The pro-nymphs (stage I larva) emerge in two days and grow into the stage II larva or nymph. Both stages extensively feed along with the adults to grow to almost the same size as the adults. The thrips lacerate the parenchyma cell walls, inject saliva and suck back the cell content. They fall into the soil crevices and pupate. Adult hibernation in soil in winters is common. Two to three generations in cotton crop are expected through crop cycle. This is parthenogenetic species. Male formation is rare. They flourish in early crop season, whenever the humidity is low (Dahiya and Singh 1982). Monsoon rains wash them out and the thrips population is naturally suppressed.

11.2.2 Insect Pests Damaging Fruiting Bodies

The bollworms form the major polyphagous lepidopteran insect group that have successfully exploited cotton crop over several decades. These include spiny bollworms, spotted bollworms, *Helicoverpa* bollworms and pink bollworms (Table 11.1).

Plate 11.6 (a) 1st instar
(b) 2nd instar (c) Adult (d)
Damage symptom of
Thrips, *Thrips tabaci*
Lindeman



These commence damage to the fruiting bodies from the time the plant has pinhead square formation. The moths get the cue for egg laying from the flower buds that are at varying stages of growth and lay eggs.

11.2.2.1 Spiny Bollworm, *Earias insulana* (Boisduval), and Spotted Bollworms, *Earias vittella* (Fabricius) (Syn. *E. fabia* Stoll) (Lepidoptera: Nolidae)

In India, early-season pests of cotton crop that become terminal shoot borers are spiny bollworms (Plate 11.7a) and spotted bollworms (Plate 11.7b). These pests were of common occurrence till the widespread cultivation of GM cotton hybrids with Bt delta-endotoxin-expressing genes. They are seen from 35 days of crop growth in different parts of the country in American cotton (*G. hirsutum*) and *G. arboreum* and *G. herbaceum* varieties and hybrids. The spiny bollworms are predominant in drier North Indian states in irrigated crop. This species was widespread in states where *G. arboreum* and *G. herbaceum* cotton varieties are cultivated. The spotted bollworms are more widespread in distribution, having their presence in the crop in all cotton-growing states. In many ways, their early infestation as terminal shoot boring stopped apical dominance of the crop and enabled the production of sympodial (fruiting) branches. These species have geographical variation in their distribution based on weather conditions, the spiny bollworm more in northern states while spotted bollworms in central and southern region. Till the end of 1980s, these bollworms were significant in cotton crop, which had long fruiting cycles, cotton ratooning and undeterred growth of alternate host plants in uncultivated land and severity of winters. In countries, such as Egypt, this oriental pest could be displaced by the introduction of pink bollworms that continued feeding on late-season fruiting bodies and depriving the local bollworm species of food resource (Reed 1994), as always happening with invasive species that dominate ecosystems due to unbridled growth. As in equatorial Africa, this pest used to have continuous cycles throughout the year due to availability of cotton in one or the other state. However, with the introduction of seed treatment pesticides with long duration action and Bt toxin expressing GM cotton cultivation throughout India, this pest is substantially minimized in cotton.

Description

Spherical eggs under 0.5 mm diameter, light blue green. They are decorated with 30 longitudinal ridges of which alternate ones project upwards to look like a crown. The egg looks like miniature poppy or pomegranate fruit. The caterpillars are stout, spindle-shaped and measuring 13–18 mm long. They vary in colour, light brown, tinged with green and grey, distinctly pale on the dorsal line with dark brown or black spots at the base of the setae in the second and fifth abdominal segments. These larvae are characterized by fleshy tubercles, one of which is dorsal and the other lateral in position, prominently seen in the last two thoracic and all abdominal segments, each bearing one hair at its apex. In spotted bollworms, the tubercles are less prominent. Yellow to chocolate-brown pupae are seen inside cocoons, inverted boat shape and made of tough felt-like silk, dirty white to pale brown in colour,

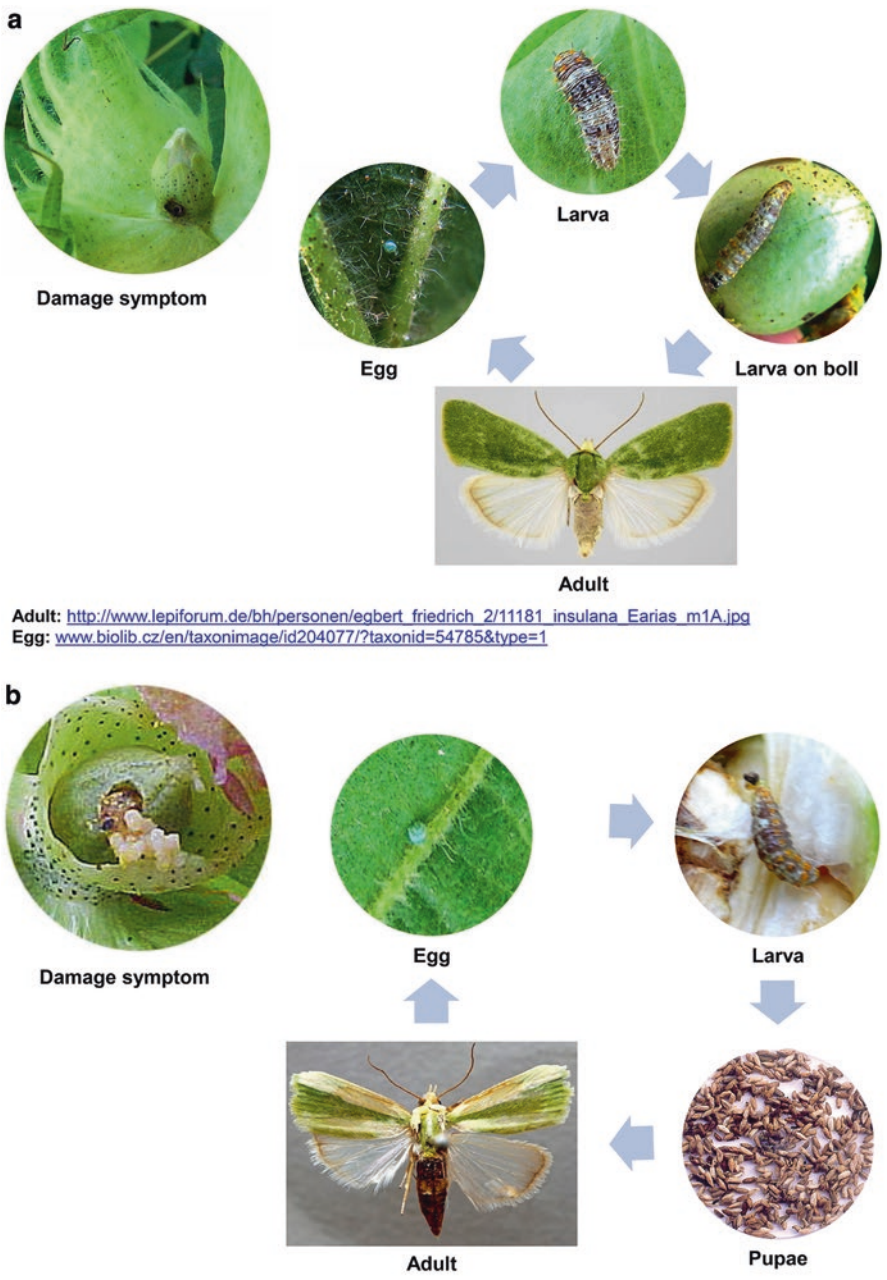


Plate 11.7 (a) Life cycle of spiny bollworm, *Earias insulana* (Boisduval). (b) Life stages of Spotted bollworm, *Earias vittella* (Fabricius)

attached to the plants or with plant debris on the ground. Colour variation based on substrate on which pupation happens is recorded (Reed 1994). The adult moth, while at rest, keeps wings snugly folded. *E. insulana* moths have pale-green wing with silky sheen due to dense scales, 20–22 mm long; the abdomen and hindwing are silvery or creamy white in colour. The spotted bollworm moths have folded forewings with creamy-white plume bearing green colour and wedge-like band crossing linearly to the wing's length.

Biology

Eggs are laid singly on young shoots and further on peduncles and bracteoles or squares (flower buds) and young bolls as they are formed. Their incubation period in summer is about three days, while larval and pupal stages could be about 13–15 days. One generation can be completed in five weeks. Variation in duration of life cycle of these insects is recorded from shorter one in equable climatic condition of tropics to longer ones in other regions, especially in winters. Their adaptation to sustain short variations in weather is well recognized (Reed 1994). Variation in the egg numbers laid by moths, emerging from white cocoons and brown cocoons; the latter has lower numbers (Mani and Krishna 1984). The Indian host plant genera, supporting *Earias* Hübner, are *Abelmoschus* Medik, *Abutilon* Mill, *Gossypium* L., *Hibiscus* L., *Malva* L., *Malvastrum* A. Gray, *Sida* L., *Urena* L., *Theobroma* L., *Corchorus* L., etc. The distribution pattern of *E. vittella* and *E. insulana* in India is dependent on weather conditions, the former avoiding cooler conditions of northern India for survivorship, indicating variation in specialization (Reed 1994) with host plants. Adaptation of life stages to weather conditions of various agro-ecologies by various species of *Earias* is noteworthy.

Propensity for stem boring, either through the growing point downwards or directly at internodes, makes it distinguishable from other bollworms. Dichotomous growth of stem by axillary monopodial buds is typical symptom in early cotton crop. The squares are fed through borehole that is blocked by excrement pellets. The damaged squares and young bolls are shed by plants. They bore on big unripe bolls from bottom. The grown-up caterpillars spin cocoons between boll wall and bracteole for pupation. *E. insulana* has four instars, while spotted bollworms have five instars. The latter species are known to pupate in soil crevices up to 30 cm depth in dry vertisol cotton-growing regions of India. The quiescent moths hide under leaves and flutter away when disturbed. Newly emerged moths feed on nectar in the extrafloral nectaries.

A number of parasitoids are recorded on both these species of bollworms (Pearson 1958), interestingly only at caterpillar stage and not in pupae. Predation records are quite low, as study on key mortality factors with predators alone on metamorphic stages is low.

11.2.2.2 *Helicoverpa* Bollworm, *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae)

American bollworm, as commonly called in India, this polyphagous noctuid pest was the single most difficult pest in cotton crop internationally. In the USA, *Helicoverpa zea* Boddie and *Heliothis virescens* (Fabricius) are the major

bollworms, while Australian cotton is infested by *Helicoverpa punctigera* Wallengren too in addition to *H. armigera*. These noctuid moths are crop pests in all the continents of the world (Fitt 1989). While the genus was earlier named *Heliothis* Ochseneheimer Matthews (1987, 1991) revised this genus and split into *Heliothis* and *Helicoverpa* Hardwick as proposed by Hardwick (1965). Their host range in cultivated crops and wild plants is extensive; the early caterpillar instars feed on foliage or green tissues of bracts, etc., and the later instars preferentially feed on reproductive fruiting parts of the plants. Hence in all host crops, their impact of damage is extensive causing crop and economic loss to cultivators (Jayaraj 1982). High mobility, polyphagy, rapid and high reproductive rate and quiescence due to both hibernation and diapause make them successful insects in all agroecologies.

Being of high economic importance in several crops all over the year, the biology of this insect pest is well worked out all over the world. Maintaining high pest pressure by this pest is seen in the cotton along with other primary hosts, such as pulses. Their resource utilization pattern on highly proteinaceous fruiting bodies makes them highly successful noctuid moths in agroecologies more than in other allied ecosystems. Often the pest has been connoted as 'man-made national pest' due to intensive agriculture for food production. It is also significant to note that their dominance in resource utilization prevents other bollworms to have equitable resource utilization. It also enhances natural enemy buildup in the crop that is useful for managing other bollworms too. In a sense, the natural cycles of various biological entities (bollworms, their natural enemies) in crop season create absolute homeostasis that the plants also adjust with to provide optimum crop yield. In case of polyphagy, it is well known that resource apportionment by this insect reduces huge damage to each of the host crop in one farmer's field. GM cotton hybrids with transgene expressing Bt delta-endotoxin were developed for cultivation due to the severe crop loss and consequent intensive pesticide use to contain that in less time span resulting in consequent ecological disasters in addition to insecticide resistance in this pest all over the world. Options of integrated pest management were focused on to see that this bollworm management in cotton becomes much more smart and cost-effective.

Description

Whitish or creamy-white eggs, subspherical with a flattened base; apical area surrounding the micropyle smooth, the rest of the surface sculptured with approximately 24 longitudinal ribs, alternate ones being shorter, with numerous much finer transverse ridges (carinae) between them are laid singly on young fruiting bodies, leaves and terminal growing tissues of cotton plants. The neonate caterpillars are translucent, with faint longitudinal lines and brown to black head capsules; the thoracic and anal shields, thoracic legs, setae and their tubercle bases and spiracles are also brown to black and giving the larvae spotted appearance. There are prolegs on the third to sixth and tenth abdominal segments. While the second instar bollworms are similar in colour with darker shades, the third instar is characterized by two colour types – green ones and red-brown ground colour, with greenish-fawn or cream- to fawn-coloured head capsule. The colour and patterns always lose

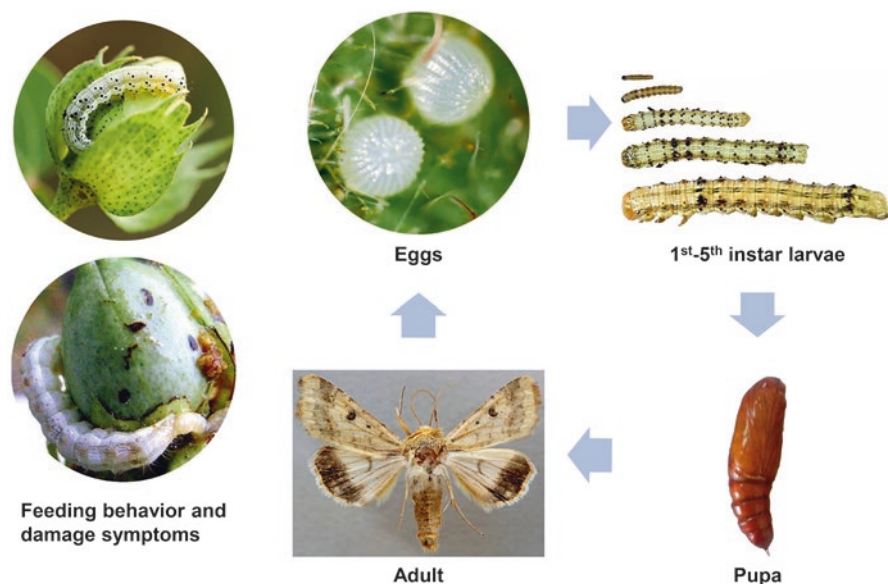


Plate 11.8 Life cycle of cotton bollworm, *Helicoverpa armigera* (Hübner)

intensity prior to each moult. The fully grown caterpillars are 35–42 mm long, the integument having granular appearance, consisting of close-set minute light brown to reddish brown, setae dark and spiracles and claws black. The colour pattern is guided by single or paired median dark with pale transverse bands, continuous broad white or yellowish lateral band bearing dark spiracles. The ventral body colour is pale yellow. The final instar has varying colours ranging from dirty brown to yellowish or reddish brown. Variation in colours of same instar larvae on the same plant is common and hence confusing. The caterpillars are cannibalistic, and in captive rearing, this behaviour increases cost and space for their mass production. With five to seven larval instars being usual, the fully grown six instars occur on cotton crop. Growth under lower temperature produces extra moults.

Pupae are 14–22 mm long by 4.5–6.5 mm thoracic width, mahogany brown and smooth surfaced, with two parallel spines at posterior spines. Larval food quality and sex determine pupal size and weight, with males being small.

The stout moths have 35–40 mm wing span and body length of 18–19 mm. Forewings are buff to greyish and light brown with dark brown or blackening markings on both wings (Plate 11.8). Females are darker than males. Moths emerge based on circadian rhythm, starting at dusk to midnight, peaking in the latter half of this period.

Biology

Oviposition is done after dusk alternating with feeding and completed by midnight. Eggs are laid singly on fruiting parts, on leaves and in growing tissues. The mother

moth selectively lays more eggs on tissues with high soluble nitrogen levels ensuring high-quality larval food. Geographic variations on the pattern of host preferences, distribution pattern and host plant utilization are seen, denoting the presence of varying races and subspecies in large populations in geographical areas (Bhattacharjee and Gupta 1972; Jayaraj 1982; Reed and Pawar 1982; Ramaswamy 1990; Fitt 1990). The adult longevity varies during season between 10 and 21 days, with females living longer over males. Quiescence to tide over summers and winters is seen in pupae.

Oviposition cue for selection of sites is a determinant of crop volatiles and its canopy colour and is known to guide even fast-flying moths for landing to lay eggs. Diel cycles of moths are well known, and they rest under the leaf of any plant during daytime and fly to feed on nectar in available plants and lay eggs in cotton. The number of eggs laid by a moth in its lifetime is about 200–500 in 10–15 days in each of the generation in cotton crop. Three to four generations are common in cotton season for this pest.

The incubation period of eggs varies between hosts and seasons within two and five days. On eclosion, the neonate eats on the chorion before taking to plant tissue epidermis. Neonate moves around to fix to the feeding sites and grow. Older caterpillars keep out posterior half of the body out of the feeding bolls and boreholes making them vulnerable for being preyed/parasitized upon. The caterpillars move between plants and within plants to extensively feed on fruiting bodies such as squares, flowers and flowers of all age. Moultings occur in the leaf surface in bright sunlight. It takes about 15–21 days in different months of cotton growth including prepupal stage. Pupation of fully fed caterpillars occurs in soil crevices. Jayaraj (1982) recorded pupal period as 2.5–17.5 days. In black cotton soils, the last stage of crop season makes these larvae to form cocoons even below 20 cm to overcome harsh summer heat. Prepupal stage is short for 1–3 days.

The moths emerge after first few showers and become active in the growing cotton crop that is at bud break stage. They lay eggs on growing squares and exploit all the fruiting forms intensely. Moths are to fly locally for great distance although their migratory behaviour is studied to indicate that a flight speed of 4.8 km h^{-1} and a median distance of 40 km per night can take them to 200 km over a week (Armes and Cooter 1991).

Pheromone of the female moth is known for this species; (Z)-11-hexadecenal with minor components of (Z)-9-hexadecenal and (Z)-11-hexadecenal-1-ol is its chemical composition (Piccardi et al. 1977; Nesbitt et al. 1979). The females on emergence after feeding release plumes of this pheromone to attract mates in the neighbourhood. Downwind pheromone plumes attract males to fly good distance to reach the females. Mated females live longer than virgin females. Males live shorter than females. Based on the availability of food, the moths can be alive between nine and 25 days. But the effective laying period shall be only two-thirds of its life. Wind speed, wind direction and moonlight on trap catch are known to influence trap catch of the moths (Vickers and Baker 1992).

11.2.2.3 Pink Bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae)

This oligophagous pest is extensive cotton pest in all cotton-growing continents and countries. Possibly originated in the erstwhile Indian subcontinent, this gelechiid insect has caused huge crop loss in both diploid and tetraploid cotton varieties. The pest moved from old world into the rest of the world through seed cotton that was commonly used to make beds and furniture cushion fillings. The damage to lint is so severe that often the crop has to be abandoned from picking as the bad seed cotton has no market appreciation. Over several decades, this bollworm threatened farmers so much that integrated pest management in cotton took roots in order to suppress it smartly and with less cost. Generations of pesticides of various chemistries could not contain the pest damage within economic thresholds, and in the beginning of this century, genetically modified transgenic cotton expressing Bt delta-endotoxin that has different modes of action on lepidopterous insects was launched for large-scale cultivation.

Description

This old world insect is oligophagous pest that is debated to have originated along with the origin of diploid cottons, such as *Gossypium arboreum* and *G. herbaceum* from the Indus basin. First reported from India in 1842, Saunders identified it as *Depressaria (Gelechia) gossypiella* Saunders from specimens of American upland cotton cultivated in Bharuch, Gujarat, in 1843. It was revised as *Platyedra gossypiella* Saunders and finally as *Pectinophora gossypiella* (Saunders). Pearson (1958) suggested this pest to have originated in Indian subcontinent. The number of parasitoids recorded in Pakistan (Cheema et al. 1980) indicates the origin of this pest to Indo-Pak region. Being of high economic importance in cotton crop across several parts of India and in all cotton-growing continents, the biology of this insect is well worked out all over the world.

Another related species under the same genus is *P. scutigera* (Holdaway), pink-spotted bollworm from Australia in the 1960s. *P. endema* Common is also an Australian species that does not attack cotton.

Biology

Singly laid or in small groups of three to five eggs, flattened oval eggs measuring 0.5 mm long by 0.25 mm width with sculptured longitudinal lines, pearly iridescent white when laid afresh, turning into yellowish and finally into orange at eclosion, with incubation period of 3.5–6.0 days. The eggs are laid in protected locations on the plant, such as axils of petioles, peduncles, lower side of leaves, old leaves at the junction of main vein, bracts, squares, flowers and 2-week-old bolls (in the sutures at boll tip or on bracteoles at the base of bolls), which ultimately become the most favoured site for egg laying (Plate 11.9). Eggs get protected from prowling predators or from contact pesticides.

The hatching is a three hour process in the early mornings. One millimetre-long, black-headed neonate caterpillars with translucent body hatch out. The neonates move to the nearest food substrates such as squares, open flowers or bolls and



Plate 11.9 Pink bollworm, *Pectinophora gossypiella* (Saunders). Adult moth: <https://commons.wikimedia.org/w/index.php?curid=9557666>

commence feeding on tissues. Second instar caterpillars have creamy-white body, dark brown head and paler thoracic shields. Third instar larvae are 6 mm long and have creamy-white body with two transverse dorsolateral pink streaks in each body segment. Those larvae that feed on flowers or on shed rotting fruit bodies have no pink colour. The fourth and final instar caterpillars measure 11–15 mm long and 2.5 mm round when fully grown. However, Watson and Johnson (1974) reported that 25% larvae had fifth instar moulting with 3 or more days' growth.

Larvae in older squares web the unopened petal rims and feed inside, causing 'rosetted' flowers. They pollinate the flowers and continue feeding on the growing bolls. Such larvae are secure and are never subjected to attack by natural enemies. This oligophage has such wonderful adaptations for survivorship and is highly successful to survive in all cotton-growing countries over centuries. Average larval period is 12–20 days, while hotter regions may have 9–14 days. Fifteen to twenty crotchets in single row, forming an incomplete circle on the third to sixth abdominal segment, are unique to this insect of cotton crop.

Mature caterpillars may be of 'short' or of 'long' cycle. The short-cycle ones proceed to pupate, while the long-cycle ones turn to diapause. Pupation is generally in soil; the mature larvae cut a round hole on boll wall and fall out into soil. They may also eat the boll wall up to cuticle, to form transparent wall and pupate there itself. The pink bollworms spin an elongated cocoon with lightly webbed exit at one end. Major abiotic conditions to convert into 'long-cycle' pink bollworms are fluctuating temperature and short decreasing photophase. Gutierrez et al. (1981) developed models to fix the time for change of field population into long-cycle ones in order to fix the chemical control action threshold. The diapause-terminated caterpillars pupated inside the same resting cocoons.

The 'long-day' caterpillars spin thick closely woven spherical cocoon, called hibernaculum, without exit hole. Mature larvae remain quiescent and curl inside the

hibernaculum for weeks or months. Towards the end of cotton season, they are seen to occupy single big seeds or unite two to three small seeds to make hibernaculum; double seeds used to be characteristically observed in northern Indian cotton, till the mid-1990s of the last century, especially small-seeded diploid and tetraploid cottons. This trend changed with the cultivation of new high-yielding cotton hybrids with large seeds. Interestingly, many larvae which spin up in the lint of open boll can spin on bales of lint after ginning, bags of seeds, cracks and crevices of buildings, etc. Birds' nests made of cotton lint also are reported having diapausing pink bollworms in West Indies (Pearson 1958).

Prepupal stage lasts for 2.5–3.5 days, and larvae turn into shining brown pupa, measuring 6–8 mm long by 2.5 mm wide. Pupae emerge between 8 and 13 days during cotton season. The greyish-brown adult moths with black bands on forewings and silver-grey hindwings emerge from pupae in early mornings or in the evenings. The nocturnal moths measure 8–9 mm long with 15–20 mm wing span. Sex ratio in cotton fields is 1:1. They are attracted to mercury vapour lamp and black light as much as to molasses and fermented brew. After feeding on nectar, they mate at three ft candle-light intensity in the first night after emergence, on crop canopy leaves, and in the shade during moonlit nights (Ingram 1994). Oviposition starts from the second night after emergence and peaks by the third night to release 80% eggs. One hundred to five hundred eggs, based on size and longevity of female moths, are recorded under ideal conditions. Adult longevity varied between five and 31 days. Short cycle-derived moths in India lived for 7–9 days, while it was 14 days in the USA. High humidity prolonged adult life, while increasing temperature reduced longevity. The moths are known to disperse through both long-range and short-range movement.

Damage

The damage to fruiting bodies of cotton crop is extensive due to the feeding of pink bollworms. Cotton plants produce three to six flushes of reproductive bodies in the active phase when the lint quality is at its best. The pest feeds on the seeds affecting the growing lint. Immature fibres with poor technical property make the country lose valuable raw material for textile industry. Its discolouration due to excrements of the caterpillar as also due to microbial growth reduces market value of cotton. Twelve to twenty percent damaged lint is the national loss of marketable lint each year. With the advent of GM cotton cultivation, this has been narrowed to 3–5%. Cotton farmers lose money when they sell infected seed cotton which fetch very low price.

11.2.3 Other Foliar and Minor Pests

11.2.3.1 Tobacco Caterpillar, *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae)

Description

The tobacco caterpillar, *Spodoptera litura* (Fabricius) (Plate 11.10), is seen to infest cotton in different states during certain years. It is widely distributed in all cotton-growing states. The eggs are spherical, somewhat flattened and 0.6 mm in diameter. They are usually pale orange brown or pink in colour, laid in batches and covered

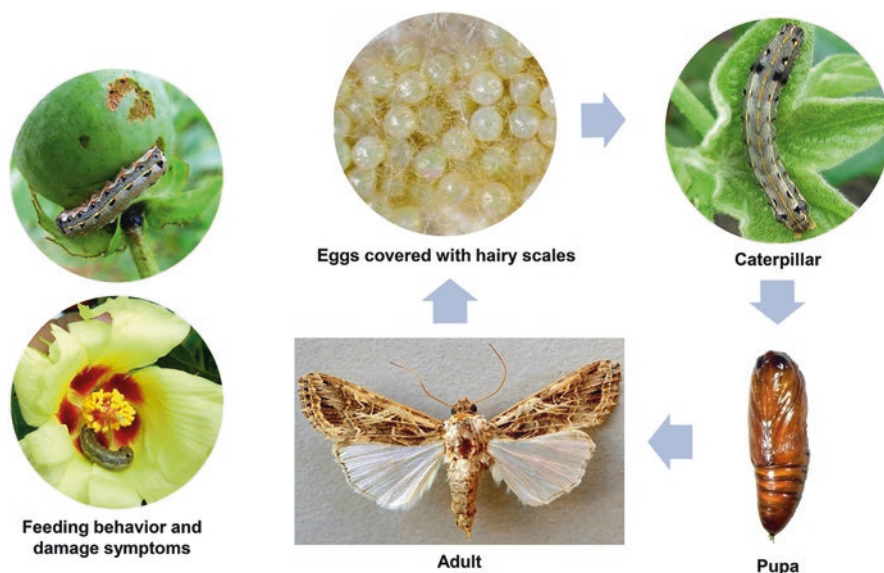


Plate 11.10 Tobacco caterpillar, *Spodoptera litura* (Fabricius)

with hair scales from the tip of the abdomen of the female moth. Egg masses measure about 4–7 mm in diameter and appear golden brown because they are covered with body scales of females. The larva is smooth bodied, variable in colour (young larvae are light green, the later instars are dark green to brown on their backs, lighter underneath); sides of body with dark and light longitudinal bands; dorsal side with two dark semilunar spots laterally on each segment, except for the prothorax; spots on the first and eighth abdominal segments larger than others, interrupting the lateral lines on the first segment. Though the markings are variable, a bright yellow stripe along the length of the dorsal surface is characteristic of *S. litura* larvae. Larval instars can be distinguished on the basis of head capsule width, ranging from 2.7 to 25 mm. Body length ranges from 2.3 to 32 mm. The pupa is 15–20 mm long and red brown, with two small spines on the tip of the abdomen. Moths have grey-brown body are 15–20 mm long, with a wingspan of 30–38 mm. The forewings are grey to reddish brown with a strongly variegated pattern and paler lines along the veins (in males, bluish areas occur on the wing base and tip); the hindwings are greyish white with grey margins, often with dark veins in *S. litura* (but without in *S. littoralis*). Eggs and young larvae are visible of leaves during the day. Older larvae feed at night and can be found during the day in the soil around the base of the plant. Adults are nocturnal, are strong flyers and are attracted to lights.

Biology

Egg masses (4–7 mm diameter), laid at night in clusters of 200–300, are covered with the brown scales of the adult. The eggs take 2–3 days to hatch. The caterpillars cluster together, feeding on the surface layers of the leaf. If the leaf is inedible, they

drop on silken threads and are carried elsewhere on the wind. Larvae are variable in colour. The young larvae are pale green and later instars are dark green to brown. Although colouration is variable, the bright yellow stripe along the dorsal surface is characteristic. The older larvae are night feeders but usually remain on the plants during the daytime. The larvae go through six instars (although five and seven have also been reported) lasting from 13 to 30 days, depending on temperature. Pupation takes place in the soil close to the plants. The pupal period lasts 7–10 days. The adults are greyish brown and 15–20 mm long with a wingspan of 30–38 mm. The forewings are grey to reddish brown with a strongly variegated pattern and paler lines along the veins; the hindwings are greyish white with grey margins. Females mate 3 or 4 times during their lifetime and lay up to 2500 eggs (Waterhouse 1993; Hill 1975). This pest has a number of natural enemies in cotton agroecosystem. Inundative release of egg parasitoid, *Telenomus remus* Nixon and *Chelonus heliconiae* (blackburni?) (Patel et al. 1979), has been found to attain the pest suppression effectively in the crop.

11.2.3.2 Leaf Roller, *Syllepte derogata* (Fabricius) (Lepidoptera: Crambidae)

Description

The cotton leaf roller (Plate 11.11) is distributed in rainfed cotton-growing states. The moths lay eggs on the leaves, which hatch greenish-white, semitranslucent caterpillars. They feed on the epidermis and cortex of leaves. The obdect brown pupae

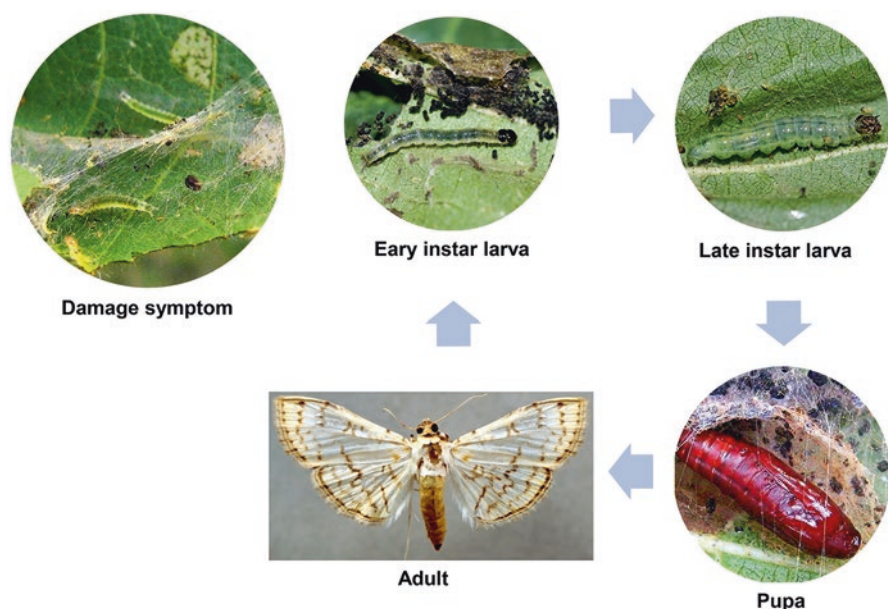


Plate 11.11 Life cycle of leaf roller, *Syllepte derogata* (Fabricius)

in these leaf cases possess eight straight spines with hooked tips. Moths are light cream in colour; the wings are traversed by many brown or black wavy lines and with grey fringe. The head and thorax have black dots; the abdomen has brown rings. The abdomen of the male is more slender than that of the female. The life cycle was completed in around 25 days.

Symptoms of Infestation and Damage

Large-scale damage gives a pale look of crop with rolled leaves and stunted growth. The pest frequently occurs in unclean farms with shaded areas. A number of natural enemies suppress this pest effectively; these include parasitoids such as *Apanteles* sp., Ichneumonoidea, etc. and predators such as assassin bugs, *Canthecona furscellata* (Wolff), etc. It is always believed that early-season occurrence of this pest shall enable the multiplication of an array of natural enemies of bollworms. It is also a pest of okra.

11.2.3.3 Green Semilooper, *Anomis flava* (Fabricius) (Lepidoptera: Noctuidae)

Description

Greenish-yellow semi-looping caterpillars (Plate 11.12) are seen to defoliate young cotton plants. This caterpillar is long and green, with yellowish bands between segments. Due to the missing of one pair of prolegs, it moves like a looper, although not related to the true loopers. Brown obtect pupae are seen with a thin cocoon and seen inside rolled-up leaves. The adult moth is brown, with an outlined pale spot near the middle and zigzag lines across each forewing. The eggs are flat and greenish. They are laid on the undersides of leaves of a food plant, besides the veins.

Symptoms of Infestation and Damage

Leaf area is significantly lost. However, the defoliation of hirsutum varieties after 25 days of growth stimulates reproductive phase in the crop. The pest is seen active at the boundaries of the crop field.

11.2.3.4 Cotton Semilooper, *Tarache notabilis* Walker, *T. opalinoides* Guenée and *T. marmoralis* Fabricius (Lepidoptera: Noctuidae)

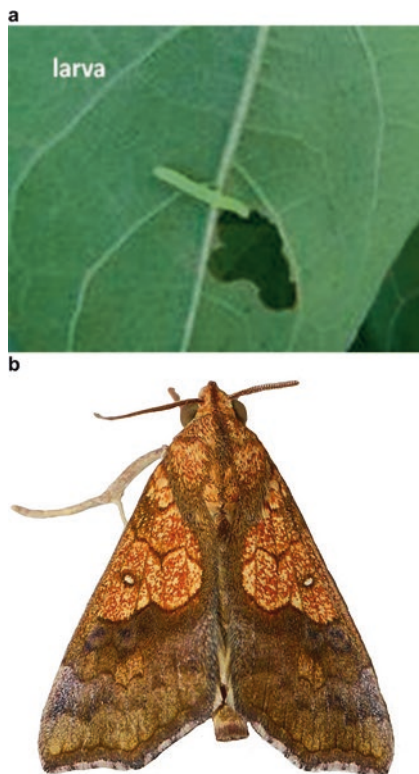
Description

Cotton semilooper caterpillars (*Tarache* spp.) have been in the cotton crop feeding on leaves and affecting the photosynthetic area of cotton crop during its growth phase. This is commonly seen in cotton-growing irrigated areas in central and northern states. Dark green fully grown larvae are 40 mm long, with six pairs of black and bright yellow spots on the dorsal side. Stoutly built adult moth with grey and brown spots on forewings lays green round eggs singly below leaf surface.

Biology

The eggs that are laid on the hind surface of foliage hatch out in 2–4 days, and these caterpillars are voracious feeders of leaf tissue (Mathews 1994b). Within a fortnight, fully grown caterpillars descend down and form pupation cells within 3 cm

Plate 11.12 (a) Larva of green semilooper, *Anomis flava* (Fabricius) (b) Adult of green semilooper, *Anomis flava* (Fabricius) (Courtesy: ICAR-NBAIR, Bengaluru)



depth in soil. Pupation period is about 2 weeks and moths emerge in 5–14 days. Four to five generations in one season are noticed. Their natural enemies such as tachinid larval parasitoids such as *Actia monticola* Mall and *Exorista seviloides* Bar and predation from *Canthecona furscellata* (Wolff) and many other geocoreid and coreid bugs suppress population in the crop.

11.2.3.5 Bihar Hairy Caterpillar, *Spilosoma obliqua* Walker (Lepidoptera: Arctiidae)

Description

This sporadic polyphagous pest has occasionally been serious on many crops including cotton in various central and northern states. Denudation of the plants is severe in large-scale invasion (Arora et al. 2001).

Biology

Breeding in summer months, they are active till November. Pupal stage is utilized for over-summering amidst plant debris. Female moth lays between 400 and 1200 green eggs in clusters below leaf surface. Eggs hatch in one week. Gregarious in the early phase, dispersal for active feeding on the crop makes them grow to 40–45 mm

in length with profuse long greyish hairs. Silken cocoons in plant debris are spun for pupation, lasting for 7–15 days. Three to four generations occur annually.

11.2.3.6 Leaf Perforator, *Bucculatrix loxoptila* Meyrick (Lepidoptera: Bucculatricidae)

Young larvae of this pest hatch out of brownish eggs in about four days and mine into leaves. Leaves are left skeletonised (Mathews 1994a). This minor pest is sporadically seen in cotton crop.

11.2.3.7 Serpentine Leaf Miner, *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae)

Adult flies are black and yellow in colour. Scutellum is distinctly yellow in colour. The maggots become leaf miner through tunnels into cotton leaves and form serpentine mines and feed at the end of the tunnel. The seedling stage of plants could succumb to the infestation. The fully grown maggots fall into the soil and pupate in the ground. Leaf surface bears punctures of the epidermis, and the greenish-white mines with linear grains of frass inside the mines can be seen. Flies emerge from pupae in 7–14 days. Eggs hatch in two days. Many leaves may bear many eggs on the same plant (CABI 2015).

11.2.3.8 The Cotton Stainer Bugs, *Dysdercus* Audinet-Serville (Hemiptera: Pyrrhocoridae)

Cotton stainers occur throughout the tropics of each continent from where they have moved to southern subtropics. Developing cotton bolls are fed by them causing immature lint and secondary infection due to microorganisms. They feed on cotton seeds and make them unviable as well as reduce their oil content (Broodryk and Mathews 1994).

There are three species recorded in India. These are *Dysdercus koenigii* (Fabricius), *Dysdercus similis* (Freeman) and *Dysdercus cingulatus* (Fabricius). There are 11 species in Africa and 21 species in both the American continents. *D. sidae* (Montrouzier) occurs in Australia. Both imago and adult stages feed on cotton plants.

Description

Ovoid eggs 1.5×0.9 mm with smooth chorion; creamy white to orange colour according to age of the eggs, as embryo develops inside, is seen. There are five instars for nymphs and the adult colour patterns of red and black gradually darken. Adults are elongated, 15 mm long and 4.5 mm broad (Plate 11.13). Head is red or reddish orange with white prothoracic collar. Antennae are two-thirds of the body length; the rostrum is folded ventrally and reaches up to the second abdominal segment.

Biology

Eggs hatch in five days. After eclosion, the young nymphs disperse for food. They have the habit of congregation around ripe and decaying fruits and seeds. Moisture

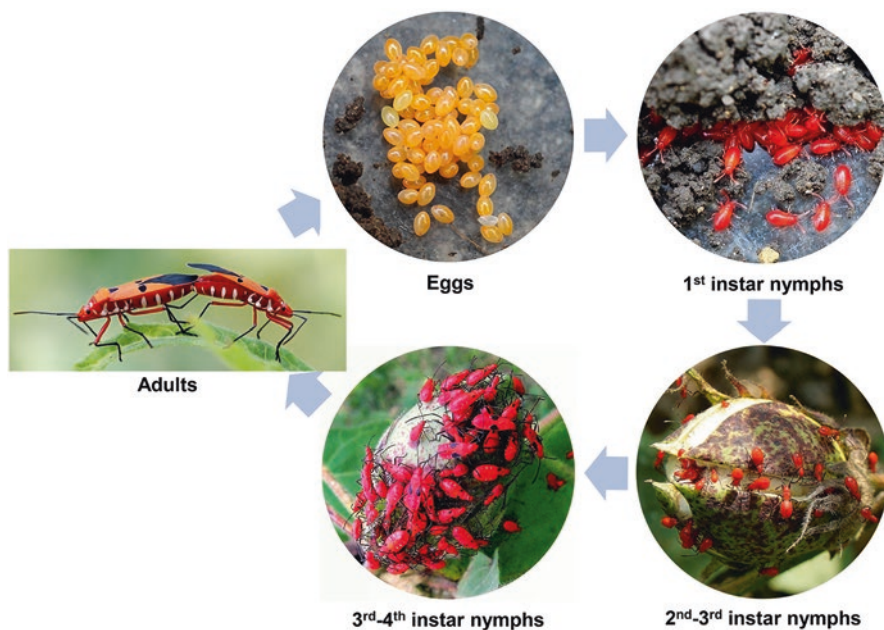


Plate 11.13 Life stages of Red cotton bug, *Dysdercus cingulatus* (Fabricius)

due to dew, rainwater and nectar from flowers and extrafloral nectaries is utilized to penetrate dry seeds and other plant parts. The nymphs moult in faster intervals during warmer period of crop production. The adults mate about two days after emergence and remain paired until oviposition occurs 3–8 days later. Eggs are laid in debris and soil, ranging from 300 to 450. They breed throughout their lives and are limited by low temperature and lack of food. The adults are noticed to fly to about 15 km, and feeding is restricted to plants of the Malvales group.

Predators, such as *Eocanthecona furcellata* (Wolff) and reduviid and geocoreid bugs, feed on nymphs and adults, while soil predators, like carabids, feed on eggs and nymphs.

Damage

They may start feeding with young flower buds, flowers and then young bolls. The growing bolls with buttery content in them are fed aggressively by a number of bugs. These fruits open prematurely, and they continue feeding on the seeds and immature lint, sucking the sap in them. The seeds are rendered shrivelled and unviable. The adults are capable of surviving on water after the crop season.

11.2.3.9 Dusky Cotton Bug, *Oxycarenus hyalinipennis* (Costa) and *O. laetus* Kirby (Hemiptera: Lygaeidae)

Dusky cotton bug, a minor pest of cotton, appears towards the end of November to April (Butani 1970). An insect native to African continent, this is universally

present in almost all cotton-growing countries. They feed on maturing cotton seeds and destroy their viability. They enter bolls through the borehole created by bollworms or in the dehiscent green bolls. Gregarious adults and nymphs are seen to damage the seeds (Plate 11.14). This insect is active throughout the year by feeding on wide variety of host plants. Both species of dusky cotton bug are widely distributed globally.

Biology

The adults emerged from August to November, both during day and night. Freshly emerged adults are soft, light greenish brown without any colour dimorphism between the male and female and gradually became hard in two days. Preoviposition period occupied 5–9 days, and a maximum of 25 eggs were laid by a single female at the rate of 1–3 eggs per day. Maximum period of oviposition was 16 days. Eggs are creamy white to light yellowish, oblong with anterior end slightly narrower, having minute pits on the chorion and laid in hollow scoop on the petiole. Egg turns to light brownish on the penultimate day with the two mandibles of the developing

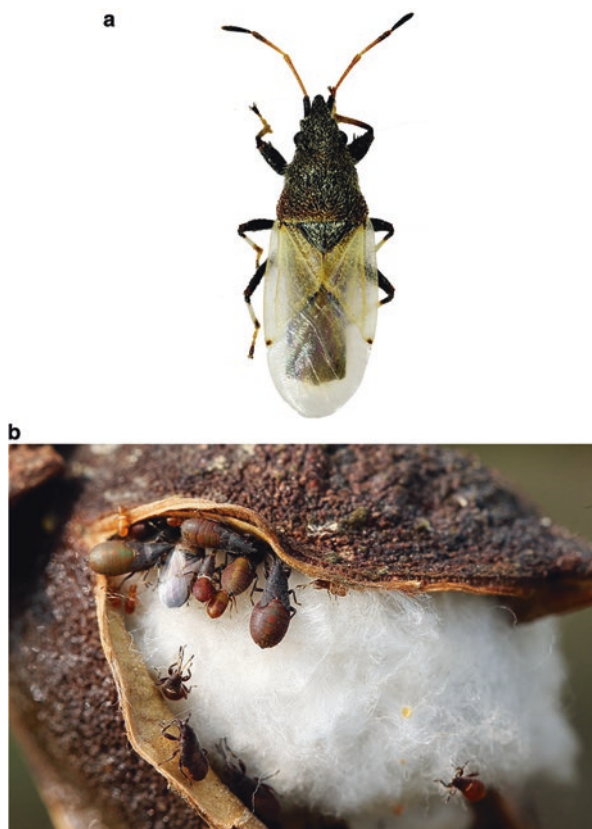


Plate 11.14 (a) Adult of dusky cotton bug (b) Nymphs and adult of dusky cotton bug

grub clearly visible through the chorion. Egg hatches in 3–6 days with an average of around four days. Fully grown grub is creamy yellow and apodous with stout, cylindrical, moderately curved and wrinkled body. Larval period varied from 48 to 62 days with an average of 55 days. However, larval period is extended in the months of November to December when it extends to 80 days. Fully fed grub stops feeding, its diameter increases and length decreases. Pupation takes place inside the stem. Total life span from egg to adult varied from 61 to 84 days with an average of 71.39 days. Adults are medium-sized and dark greyish brown with pale cross bands on elytra. Males are smaller in length and width. The gradual increase in daily maximum temperature with low relative humidity synchronized with the presence of immature cotton seeds was the most conducive condition for population buildup of dusky cotton bug on cotton (Ram and Chopra 1984). They lay eggs in open bolls, 15–20 eggs by female bugs with generation duration of 22–136 days under laboratory conditions (Hammad et al. 1973).

The population trend of *Oxycarenus laetus* Kirby was recorded on three principal hosts, namely, *Abutilon indicum* (Link) Sweet, *Sida acuta* Burm. f. and *Thespesia populnea* (L.) Sol. ex Corrêa, in relation to climatic variation (Thangavelu 1978). Population density varies significantly over the months as shown from the analysis of variance, thereby indicating that the population buildup is favoured by certain climatic factors. Weather parameters, such as temperature and relative humidity, have a very significant effect on the growth of the population. Peak population is recorded during hotter months March to July. The population is at its low ebb during colder winter months November to January. High temperature (35–40°C) and moderately high humidity (45–60%) seem to be the favoured climate for rapid growth of the population, whereas very high humidity adversely influences the population as indicated by the negative regression values obtained consistently in both years.

Damage

These bugs depend on seeds of Malvaceae for completion of development. The bugs will feed on a wide variety of plants, such as sunflower (Goyal 1974) causing damage. Greater damage is done to the seeds by reducing quality, germination and oil content (Sweet 2000; Srinivas and Patil 2004). The lint becomes weak if the bugs damage growing cotton seeds. Sometimes, the bugs are crushed in the ginning process, staining the lint.

11.2.3.10 Stem Weevil, *Pempherulus affinis* Faust (Coleoptera: Curculionidae)

Description

Stem weevils (Plate 11.15) are commonly found in cotton crop of Tamil Nadu (Parameswaran and Chelliah 1984). The pest forms gall-like swellings on the stem. This pest is found to be distributed in India, Myanmar, Thailand and the Philippines but assumes a key pest status in southern India. Its host range is cotton, okra, jute, *Abutilon indicum*, *Hibiscus rosasinensis*, *H. cannabinus* and other malvaceous and tiliaceous plants. Cotton is the most preferred host.



Plate 11.15 Shoot weevil, *Pempherulus affinis* Faust

The damage to cotton starts when plants are young and are about three weeks old. The grubs bite into the region between the bark and the main stem, resulting in swellings on the stem just above the ground level. Young plants are invariably killed on account of the attack of the pest, and the older plants that survive lack vigour and strength, and when strong winds blow, these plants break at the nodes. Due to the feeding of the grubs, the plants become completely dry. Fully grown plants survive the attack by developing a woody gall at the collar region. More than one grub is also noticed per plant, which causes multiple galls. These galls are weak points where the stem breaks if there are strong winds or if disturbed during inter-cultivation operations or due to heavy boll formation (Plate 11.15). The number of bolls per plant is considerably reduced and the lint quality is also affected. Adult weevils generally feed on the bark of the plant and lay eggs on the cotyledon nodal region. There can be 65% plant mortality, 72% reduction in boll production and 80% reduction in yield of seed cotton (Surulivelu and Rajendran 2003).

Biology

Adults are very small weevils and dark in colour with two small white patches on the elytra. Adult weevil lays globular or oval-shaped eggs singly in the cavities scrapped out by the weevil at the nodal region of the plants which are tender, soft and succulent. Grubs feed inside the stem by causing spiral galleries and damage the vascular tissue, which transports the nutrients. The infestation starts on 15–25-day-old plants. An adult lays an average number of 50 eggs up to a maximum of 121 eggs. Egg laying period varies from 60 to 80 days. The incubation period is 6–10 days. Developmental period of the grub ranges from 50 to 60 days. Grubs are white and apodous. The grub feeds on stem tissues internally. The larval period lasts 35–37 days. It pupates in pupal chamber. Pupation takes place inside the stem in a specially prepared chamber, and before turning into the pupa, the grub constructs a passage through the stem to the outside leaving only the bark intact. The pupa is white in colour at first but turns brown and emerges as adult within 10–12 days. The longevity of the adults varies from 25 to 60 days.

11.2.3.11 Shoot Weevil, *Alcidodes affaber* (Aurivillius) (Coleoptera: Curculionidae)

Description

A pest of cotton and okra crops and also found on *Hibiscus cannabinus* L. (Ayyar 1922); its grubs form galls on the stem. Adults feed on leaf buds, petioles, tender terminal portions and sometimes fruits also. Grubs do serious damage to the plant by boring the stems and side branches. Initially they feed on the tissue around the point of entry, resulting into a gall-like swelling around the site of injury. Later, they bore downwards if the eggs have been laid at the terminal end, and when the eggs are laid in side branches, the first and second instars feed inside side branches and later migrate downwards into the main stem where they finally pupate after passing through the remaining instars. Adults feed by scooping the tissue of succulent shoots towards the tip, leaf buds and petioles. The damage done by the adults is quite insignificant. The weevil appears in the field in the first week of August and remains in the field up to December. The weevil attacks only the crop raised in July, and the rainy season is more conducive for breeding. Only one generation of the weevil was recorded.

Biology

Subramanian (1959) studied the biology of the weevil, whereas Devaiah et al. (1981) described its various life cycle stages. The adults emerged from August to November, both during day and night. Freshly emerged adults are soft and light greenish brown without any colour dimorphism between the male and female and gradually became hard in two days. Preoviposition period occupied 5–9 days, and a maximum of 25 eggs were laid by a single female at the rate of 1–3 eggs per day. Maximum period of oviposition was 16 days. Eggs are creamy white to light yellowish and oblong with anterior end slightly narrower, having minute pits on the chorion and laid in hollow scoop on the petiole. Egg turns to light brownish on the penultimate day with the two mandibles of the developing grub clearly visible

through the chorion. Egg hatches in 3–6 days with an average of 4.20 days. Fully grown grub is creamy yellow and apodous with stout, cylindrical, moderately curved and wrinkled body. Larval period varied from 48 to 62 days. However, larval period is extended in the months of November to December when it extends to 80 days. Fully fed grub stops feeding, its diameter increases and length decreases. Pupation takes place inside the stem. Total life span from egg to adult varied from 61 to 84 days. Adults are medium-sized and dark greyish brown with pale cross bands on elytra. Males are smaller in length and width than those of females. Recent reports of shoot weevil from Karnataka indicate widespread occurrence in Bt cotton (Vijaykumar et al. 2011).

11.3 Integrated Pest Management in Cotton Crop

Cotton crop has been one of the best systems that enabled the research on integrated pest management (IPM) and to develop country-specific IPM packages (Kogan 1988). Both by virtue of location-specific and national research systems, such recommendations were developed and set up for adoption by cotton growers. The fundamental concept in all these has been to cultivate jassid-tolerant cotton varieties/hybrids that were bred specifically by public research institutions in India.

Cotton Herbivory As a Strategy for Pest Survivorship

Cotton pests are known to exploit the available resource of cotton crop, till they have better host plant options during the crop season. The overgrazing tendency of pests is managed by cotton crop by reducing the fecundity and increasing development cost in terms of energy on growing metamorphic stages, such as larvae and prepupae. The resultant generation may not be as robust to survive all adversities as they would have been on their primary and other natural hosts. At varying levels of gossypol and other similar phytochemicals in cotton that are mainly deployed in the tissues to thwart major depredation, the polyphagous pests manage to survive one or two generations before they switch over to other favourable hosts. Typical example to this process is the case of *H. armigera* that moves to pigeon pea in central Indian cotton-growing states when this crop commences flowering. Similarly, *Earias* spp. too move to okra and other host plants of the Malvaceae after finishing early generations in cotton crop.

Evolution of Cotton Pest Management Strategies

The country cultivated all the four cultivable *Gossypium* species. Depending upon their susceptibilities to the cotton pest spectrum, their varieties were deployed to contain such pest species from becoming major biotic stress in the cotton crop. The cotton pest management in India followed the pattern of development of pest management principles in the science of entomology. Integrated pest control and integrated pest management became the practicing phraseology among cotton entomologists of the country who recommended appropriate integration techniques of the times, developed through studies on natural control as well as interventions using chemical synthetic pesticides, based on the patterns of pest dynamics of each

crop season. The essential *mantra* was to evolve suitable pest management system to tackle bollworms that economically debilitate the farmers due to loss of fruiting bodies over the entire cotton season (Frisbie et al. 1989; Luttrell et al. 1994; Dhandapani et al. 1992; Kogan 1998; Sundaramurthy and Basu 1985). Monitoring of life stages of pests and their presence in the cotton-based agroecosystem through agroecosystem analysis (AESA) became the UN-FAO prescription for improving justification for the application of chemical pesticides in cotton. Moving from conventional agriculture with accent on utilizing natural resources for crop production, AESA-based pest management in the agriculture tried to optimize these agricultural resources in order to prevent excesses in human intervention and aimed for sustained farm productivity. Indeed, entomologists regarded insect growth and development in relation to the influence of temperature (Pradhan 1946), and degree-day accumulation in the crop season was visualized as a useful tool to predict the first appearance and buildup of pests in cotton crop. The concept of economic threshold of pests (Table 11.3) is ingrained in the planning of IPM.

Detection and population monitoring of the movement of male adults of the pests in cropping season using pheromone traps (Sharma et al. 1973) have been extensively used with various trap designs, such as delta traps, water traps, sticky traps, funnel traps, etc. (Lopez et al. 1990). The traps (Pawar et al. 1988) are generally recommended to be installed at bud break stage or as and when the first flush of eggs is noticed in the crop. The traps at canopy height with 1:1 blend ratio of isomers are performed ideally for monitoring purpose. The relationship between the trap catch of males and the presence of eggs or caterpillars in the crop did not have wide application all along the season (Pawar et al. 1988) although at low moth densities and at the early part of the season, it may work. Offseason management of the pest in okra and other vegetables does reduce the population in cotton in the ensuing *kharif* season. Cultural control by deep summer ploughing followed by irrigation is practised in irrigated cotton area. However, in dryland area, the pest carry-over is a significant issue due to lack of such feasibility. Both abiotic and biotic key mortality factors do influence the pest population structure empirically. It is seen that their adaptive resilience makes them to adjust to survivorship strategies, while natural calamities, such as heavy rainfall, drought conditions, strong winters and summers, etc., reduce

Table 11.3 Economic threshold levels (ETLs) of major cotton pests

Cotton pest	Economic threshold
American spotted bollworm	5% damaged fruiting bodies or 1 larva per plant or total 3 damaged square/plant taken from 20 plants selected at random for counting
Pink bollworm	Eight moths/trap per day for 3 consecutive days or 10% infested flowers or bolls with live larvae
Spodoptera	One egg mass or skeletonized leaf/ten plants
Jassids	Two jassids or nymphs per leaf or appearance of second-grade jassid injury (yellowing in the margins of the leaves)
Whitefly	5–10 nymphs or adults per leaf before 9 AM
Aphids	10% affected plants counted randomly
Thrips	5–10 thrips/leaf

moth population drastically. It is seen that the survivors have higher fecundity and longevity to compensate the declining population.

Managing invasive pest species became the major challenge of the present century in cotton as well as in other crops. Lessons on pest management that were learnt from the experiences of the last century did pave the way for efficient and quick response to the anomalous expansion of invasive pest species in cotton. Pesticide umbrella provided to save genetically modified Bt cotton hybrids that are only armed with bollworm tolerance from sap-sucking insects did damage the agro-ecology and reduced the biotic balance of prey-natural enemy ratios. AESA-based pesticide application had to be implemented in order to master the art of suppressing ever-increasing mealybugs and whiteflies in cotton crop, particularly in irrigated cotton-growing states. The rainfed Indian cotton farmers did manage well the exigent invasion of mealybugs by judicious management of ant movement as well as waiting for the support of natural enemies that took over the mealybug colonies in cotton crop. This lesson from rainfed cotton was transferred to irrigated cotton growers to get the realization that search for more efficacious pesticides and their continuous usage is counterproductive to sustain the economics of cotton cultivation. Carson (1962) did influence post-independent cotton pest management in India. Pradhan (1946) proposed biometer to measure pest dynamics in crops in order to plan pesticide application in agricultural crops. The barometer on the success of pest management swung unevenly from time to time due to the constant inefficacy to fight against sap-sucking, leaf-eating and fruit-feeding pests. Pesticides that are deployed could support cotton plant protection unevenly in different geographic and agroclimatic conditions (Sundaramurthy and Chitra 1992; Rajendran and Basu 1999). Hence, enhanced studies on alternative methods of pest management are to be integrated into the overall practice of pest suppression. Biological control, cultural control and, in extreme cases, mechanical control were inducted as good practices. Thus the definition of integrated pest management (IPM) toolbox became lower chemical pesticide use or no-pesticide pest management in the 1990s of the last century (Rajendran et al. 1999). The models of cotton cultivation that were developed in the last half of the 1990s of the twentieth century did provide hope for better ecological footprint in large chunks of Indian cotton farms.

Cotton Genotypes with Pest Tolerance

Susceptibility to pests was kept as criteria for developing national varieties, right from the days of its introduction that was steered by colonial system (Sikka and Joshi 1960). The Central Cotton Committee had directed breeding programme for various cotton-growing provinces of those times. The *G. hirsutum* (upland cotton, American cotton) was the preferred cotton species that was used for commercial cultivation. Their varieties with American blood were highly susceptible to jassids. The efforts to breed for jassid resistance became a natural choice of breeders in order to economically cultivate such varieties all over the country (Singh et al. 1999). Employing various breeding techniques to introgress genes that offer resistance to sap-sucking insects, such as jassids, by making the leaves and tender stems to be *hirsute* (hairy) could provide good jassid tolerance in cotton varieties (Singh

and Narayanan 1999). The advent of heterosis cotton breeding (Bhale 1999) in dry-land cottons during the 1960s directed the development of early cotton hybrids with genetic improvement of economic attributes of the fibre and resistance to major pests and diseases. The number, density and angle of pubescence on the foliage and plant parts made the impediment for jassid feeding and multiplication. Thus one set of common, polyphagous pests, jassids, could be tackled in Indian cotton varieties. The pesticide application to suppress excess damage by jassids could be thus reduced in cotton. The dominant pesticides for this purpose were contact organo-chlorine and organophosphate pesticides. It was also appreciable that such hirsute varieties were strongly supporting many natural enemies of cotton pests. Cotton plants are well known to take up compensatory growth (Sadras 1995) when the reproductive fruiting forms are lost due to damage by pests and other factors. Sustained production of new fruiting forms also becomes reservoir of resource for cotton pests. Biochemical defence of cotton plants due to gossypol in tissues especially of the buds, flowers and fruits has been well recognized. The bollworms have higher energy investment due to detoxification of such phytochemicals in cotton. Oligophagous cotton pests are genetically adapted to such defence chemicals, while polyphagous ones have to activate the physiological adaptation to survive on cotton and move on to other crops, such as pulses, vegetables, etc., according to seasonal availability (Rajendran et al. 1999). Integrated pest management designed to opportunistically integrate tools available in the IPM toolbox was advocated in crops (Luttrell et al. 1994; Kenmore 1997; Sundaramurthy and Gururajan 1992).

Host plant resistance has been pursued in large measure (Sundaramurthy and Gururajan 1992; Rajendran and Basu 1999) by cotton breeders to incorporate tolerant hostplant traits, such as okra leaf types, frego bracts, glabrous leaves, etc. (Kennedy et al. 1987). However, the glabrous leaves and such many traits that offer bollworm resistance did not support jassid tolerance, and these progenies became highly jassid susceptible types in India. Breeding for resistance has been an enabled approach that gave good sources of resistance to be incorporated into cultivated cotton genotypes. Gene transfer for incorporating the desirable genes that offer resistance against cotton pests has been an ongoing process of cotton improvement from the time commercial cotton is under production in commercial format. The cotton varieties and hybrids that were notified for cultivation did possess high tolerance of jassids and aphids. Table 11.4 provides details of the tolerance in Indian cotton varieties and hybrids.

Table 11.4 Indian cotton genotypes that possess moderate tolerance to pests

Pests	Cotton varieties	Cotton hybrids
Jassids	Bikaner Narma, ABH-466, H-777, G.cot-12, G.cot-10, RS-875, RST-9, F-5-5, Fateh, RS-2063, Sumangala, Supriya, CSHH-198, CSHH-298	Hybrid-4, JKHy-1, H-6, NHH-44, Savita, H-8, PKVHy-2, Surya, H-10, RCH-2, Ankur-651, Kirti, G.cot-11, G.cot DH-7, G.cot DH-9, MDCH-201, CISSA-2, CISA-310,
Whitefly	Supriya, Kanchana, LK-861, RS-875, RS-2013, CSHH-198, CSHH-298	Savita, Surya, RCH-2
Bollworms	LH-900, F-414, Abadita, RS-2013	—

Synthetic Chemical Insecticides for Cotton Pest Suppression

Various spectra of chemical groups and chemistries have been deployed in cotton crop to suppress caterpillar populations during peak squaring and boll formation stages. Organochlorinated, organophosphate, carbamates, synthetic pyrethroids, neonicotinoids, synthetic avermectins, spinosad from spinosin, etc. have been used in various decades of the last century. Insecticide resistance was the strongest lesson that was given to farmers by this pest for injudicious pest management approach. Although a recessive trait in insects, insecticide resistance gets magnified due to the destruction of susceptible populations and consequent anomalous expansion of recessive trait of insecticide resistance.

Integration of Chemical Pesticides

Cotton crop has been the one on the globe that exhibited the biological and ecological elasticity of pest organisms to sustain and surmount adverse conditions, such as pesticide chemistries. Human endeavour to get maximum profit out of crops by deploying inputs, such as agrochemicals including fertilizers and pesticides, was not fruitful. The commonly recommended pesticides against cotton pests are given in Table 11.5.

Table 11.5 Control of cotton pests with pesticide chemistries

Name of the pest	Pesticide chemistry	Formulation dosage per ha
Sap-sucking pests	Neonicotinoid chemistries	Seed dressing at 5–10 g per kg cotton seed using:
	Systemic organophosphate chemistries	Imidacloprid 70 WS
		Thiamethoxam 75
		Acetamiprid 20 SP
		Spraying of organophosphate pesticides such as methyl demeton/dimethoate/quinalphos, etc. at 2 l/ha, fipronil 5 SC at 1.5 l/ha
		Acetamiprid 20 SP at 50 ml/ha, thiamethoxam 25 WG at 100 ml/ha
Whitefly	Organophosphate and neonicotinoid pesticides	Triazophos at 2 l/ha, phosalone 35 EC 2 l/ha, thiamethoxam 25 WG at 100 ml/ha
Bollworm and other caterpillars	Neonicotinoid chemistry	Thiodicarb 75 SP 750 g/ha
		Indoxacarb 15 SC at 500 ml/ha
	Avermectins	Emamectin benzoate 5 SG at 50 g/ha, abamectin 1.8 EC at 50 g/ha
	Spinosyn	Spinosad 48 SC at 150 ml/ha,
	Phthalic diamides	Flubendiamide 480 SC at 10 ml/ha
	Anthranilic diamide	Chlorantraniliprole (Rynaxypyr) 18.5 SC at 150 ml/ha

(a) Pesticide seed treatment to protect crop from early-stage pests

Seed treatment using systemic pesticides (Almand 1995) and microbial biopesticides (Anonymous 2010) offers a great tool to reduce pesticide load in crop environment, while assuring target-specific application, in spite of various inept and inefficient on-farm practices in India. Cotton crop with such seed treatment is a model to study sustained stability of agroecology. Combination of seed treatment with systemic pesticides along in GM cotton hybrid seeds was unique to manage both early-season buildup of sap-sucking pests and subsequent caterpillar invasions on fruiting forms of cotton for over 45 days. Their initial buildup in the crop is used to seed a new cohort to successfully establish along the season. It is noteworthy that this group of pests could be sustainably managed by integrating pesticide seed treatment with GM technology cotton hybrids during the last decade in India. Since the modes of action of seed-dressed pesticides and plant-expressed delta-endotoxin are different in these caterpillars, the scope of resistance development of this pest is not expected to be soon. The sublethal concentration of those systemic pesticides in the crop towards the later phenology stages could initiate pesticide resistance physiology in cotton pests. However, the seed treatment practice by cotton farmers using specific pesticide formulations that are registered for seed treatment is not satisfactory for want of efficient appliances for perfect pesticide seed treatment. The spurt in thrips population in cotton seed treated with imidacloprid that was discovered by Elbert et al. 1990 and was recorded in India as much as in other countries (Dobbs et al. 2006; Hossain and Baqui 2010).

(b) Pesticide resistance in key pests

Melander (1914) proposed for the first time the potential possibility for insects to resist pesticides based on his experiments in three locations for one year in San Jose scale insects. The excessive faith to depend on chemical control for pest management in agricultural farms during those decades when synthetic organic insecticides, such as DDT, was adored as the best bet for winning over the battle on the ever-multiplying insect fauna on human living system was Carson's (1962) *Silent Spring*. This book had a profound revisionist cultural effect to stir environmental consciousness. The result of continuous and sustained application of agrochemicals to suppress bollworm buildup during cotton season has resulted in adverse micro- and macro-ecological impact in agroecosystems. Induced selection pressure due to sustained application of pesticides in crops including cotton induced the pest genetics to react back and become resistant to almost all the chemistries man invented and deployed over the last two centuries. When agriculture has been growing in order to meet the sustained demand for food, feed, fodder, fibre and all other human requirements, the setback due to wanton use of pesticide chemistries of their non-efficacy did provide new thinking about the packages of practice for such purposes. The detailed scientific analysis on the reasons of non-efficacy (Brown 1968; Kranthi et al. 2000; Kranthi 2005; Mathews 1994b) resulted in the concepts of insecticide resistance in insects and other target and even nontarget pest organisms. The

scientific advancement in this area of research provided landmark insight into the genetics of pesticide resistance in these animals. The trigger to incite the recessive genes that enable the cotton pests, such as bollworms, to develop physiological adaptation to prevent the mode of action of the given pesticide chemistry was elucidated in the early 1980s and 1990s of the last century.

The pesticide industry as that of the global players did bring out such combination products of pesticides such as organophosphorus chemistry with synthetic pyrethroid group chemistry in order to exploit the benefits of both modes of action such as knockdown and kill due to various cholinergic esterase enzyme blocks. However, it was soon shown by the pest insects that they are highly adaptive to such selection pressures too with the result that in many instances, most of the pesticides and their specialty formulations of mixtures were to be obliterated with new chemistries. The watershed in pesticide chemistry research was the development of neonicotinoids and many synthetic products of various natural xenobiotics, such as spinosin, avermectins, etc. Scientific advancement for the search for alternate chemistries with low impact on environment did flourish to bring out 'green' chemistries. However, due to their high toxicity, most of them, such as abamectin and spinosad, became red-triangle pesticide formulations, challenging the 'green chemistry' concepts. The challenge to sustain commercial agriculture with sustained profitability could be supported by scientific advancements for new pesticide chemistries with higher efficiency of pest suppression. Biotechnological solutions to toxify plants with insecticidal proteins and other similar approach did provide high investment to anticipatory mitigation of the perceived potential adaptation of pest insects against the pesticide chemistries. However, the battle seems to swing to the nature's side since genetic adaptations of organism to sustain and surmount selection pressure become the best evolutionary strength to species survival in this planet.

Sims et al. (1996) reported monitoring strategy for early detection of resistance to Bt insecticidal proteins (Ghosh et al. 2001) in caterpillars. In the recent years after over a decade-long cultivation of single gene- and multiple gene-bearing GM transgenic cotton hybrids with Bt delta-endotoxin-expressing gene families, India has seen the return of pink bollworm that is reported to have resistance to all these gene products (Kranthi 2015). Right before the commercial launch of Bt hybrids in India, reports of potential differential response in lepidopteran pest populations across India in different strains of bollworms were published (Kranthi et al. 1999). Wary of pesticide resistance to bollworms in cotton crop, the concept of genetically modified (GM) cotton was brought in by genetic transformation with delta-endotoxin-expressing gene from *Bacillus thuringiensis* Berliner (Bt) bacterium. The concept of bollworm resistance to GM cotton with Bt delta-endotoxin gene is described elsewhere.

Integration of Natural Enemy Systems and Biological Control

The use of microbial pesticides got boost in the environment of increased pesticide resistance in various bollworms in cotton-growing countries. Biological control (King 1994; Bellows and Fisher 1999) by naturally occurring parasitoids, predators and insect pathogens has excellent control on this bollworm population (Table 11.2).

Inoculative and inundative release of target species into the crop to suppress the build of definitive pest species could be recommended. Providing these natural enemies from the bioagent production factories to farms for inundative release during each season such as synthetic chemical pesticides was able to reduce pest load in cotton crop. Generally egg parasitoids, such as *Telenomus remus*, trichogrammatids and egg-larval parasitoids, do play a role in affecting their structure (King 1994). Larval parasitoids (*Apanteles angalati* (Muesebeck), *Campoletis chloridaeae* (Uchida), *Steinernema* spp.) and larval-pupal parasitoids (*Chelonus blackburni*, *Carcelia illota* Curran) do have significant influence to reduce populations in cotton fields provided the insecticide application is judicious. Predators such as green lacewings (*Chrysoperla carnea*, *C. zastrowi-arabica*), *Polistes* spp., pentatomid (*Canthecona* sp.) bugs, reduviid bugs, *Nabis* spp., *Orius* spp., *Geocoris* spp., beetles such as Coccinellidae and Carabidae, formicid ants and a number of saltatory spiders and a spectrum of predatory birds, such as mynahs, egrets, river terns, king crow, etc., are common in cotton crop during every season. Biological control of pests using egg parasitoids (Sithanantham et al. 2013) has been an encouragement for suppressing the lepidopteran pests of cotton and other crops. The planning associated with agroecosystem analysis to find out the optimum time that is desirable for deploying egg parasitoids in cotton is the key for supervised pest suppression in farmers' fields. Successful insectaries supplying egg parasitoids have been an economic example that is to be highlighted as major outcome of Indian public research in the last decade of the last century. Emulating the cotton cultivation in countries, such as Uzbekistan, this tactic of IPM of commune farms, being catered by large insectaries supplying trichogrammatids to cotton, was a good success story in India. The deployment of *Nomuraea rileyi* (Farlow) was suggested by Ignoffo (1981). Entomopathogens that naturally occur on caterpillars which are *N. rileyi*, *Beauveria bassiana* (Bals.-Criv.) Vuill., *Metarhizium anisopliae*, *Aspergillus* spp. and nuclear polyhedrosis virus specific to *H. armigera* are found in cotton fields. Recommendations for the use of fungal insect pathogens, such as *Metarhizium anisopliae* (Metchnikoff) Sorokin, *Beauveria bassiana* and *N. rileyi*, and commercial bacterial pesticide preparations like that of soil bacterium, *Bacillus thuringiensis* and nuclear polyhedrosis/cytoplasmic polyhedrosis proved useful in central and southern Indian states. Inundative release of eggs of green lacewings and eggs of *Trichogramma chilonis* Ishii along with application of *H. armigera* nuclear polyhedrosis virus (HaNPV) could be a good integration of biological control tool in the IPM toolbox.

Looking back to contemporary recommendations such as legislative prevention of uprooting cotton crop after economic harvest and ban on ratoon cropping of cotton alongside clean cultivation practices that were directed to avoid carry forward of pest survivorship in farms, the use of available systemic pesticide chemistries, monitoring of adult movement in crops and scouting for eggs and caterpillars have been effective tools in the available cotton IPM toolbox. Reducing window of ginning season could reduce diapausing pink bollworms. Destruction of alternate hosts of pests from farm periphery shall be an ideal solution to reduce the scope of their offseason survival. Sustained pest pressure due to susceptibility of crop varieties, weather conditions and crop agronomy could be tackled using such tools. Paramount

aspect of cotton IPM was a balancing act between tactics to suppress early-season sap-sucking pests without seriously disturbing natural enemy complex that takes over the anticipated invasion of bollworm complex during every season by manipulating the nutrient supply system as well as by nurturing natural enemy complex in cotton farms in addition to sustaining minimum herbivory in the crop. India's cotton breeding strategy to exploit tangible tolerance in cotton varieties to sap-sucking insects, particularly jassids, did support bollworm IPM design. The redefined economic threshold of pests is given in the Table 11.4.

Phytochemicals for pest suppression became another biological approach for IPM deployment. Use of botanical pesticides, such as neem seed kernel extract at 5%, azadirachtin (1000–3000 ppm) formulations at 2 l/ha and neem oil or karanj oil at 1%, having antifeedant/deterrent properties is recommended against sucking pests as well as bollworms. These botanical mixtures serve the purpose of making the host plant tissue unpalatable due to repellence, antibiosis or at times adverse physiological response on the insect pests such as interference in gustatory stimuli or moulting process, according to the exposed concentration to the target pest. Due to unabated non-efficacy of chemical pesticides to effectively reduce pests in cotton crop, farmers innovated on the use of locally extracted preparations containing crushed garlic, green chillies and leaves and fruits of certain plants that have toxic principles for pest management in cotton crop. However, high photo-instability, suspected quality in marketed products and inconsistent pest control efficiency in different agroclimatic regions are serious problems before being incorporated as robust component in IPM (Vennila 2008). Such biological measures that were adopted in cotton did reduce the selection pressure due to chemical pesticides on pest population.

Organic Cotton

In the quest for reducing pesticide load in cotton, integrated pest management was taken up with thrust on designing crop agronomy with the crop's capacity to keep sustained nitrogen absorption (Tarhalkar et al. 1996) and thereby reduce the attraction of bollworm moths to lay eggs; the egg-laying threshold was determined to be 1.5 mg/g terminal leaf tissue from long-term fertilizer cotton trials (Tarhalkar et al. 1996; Venugopal et al. 1996; Rajendran and Soth 1997, 1999). The result was the development of an ideology of cotton crop cultivation in rainfed areas of central India to produce chemical-free cotton that was widely taken up (Rajendran et al. 1999) and has improved the ecological footprint in the region. The principles of pest management under IPM became more lucid to farmers who practised this, and today India produced the largest quantity of this type of cotton in the world.

Genetically Engineered Cotton for Bollworm Tolerance

Sea change in the recommended management practices of bollworm suppression has happened in this century due to advancement of technology in plant protection science. Indian cotton farmers were offered the genetically modified (GM) cotton (Bollgard I cotton) bearing the gene expressing delta-endotoxin gene, *cry1Ac*, of *Bacillus thuringiensis* (Bt), an ubiquitous soil bacterium since 2002, and,

subsequently, Bollgard II cotton with stacked *cry1Ac* and *cry2Ab* genes (Choudhary and Gaur 2010). Cry family of endotoxin-expressing genes of Bt has been explored for pesticide expression in plants, and mode of action in insects was studied (Ghosh et al 2001; Li et al. 1991; Cygler et al. 1995; Grochulski et al. 1995; Bravo et al. 2007; Pigott and Ellar 2007). Over a period of 13 years, the impact of continuously cultivating GM cotton has been analysed to recognize the development of bollworm resistance to the expressed delta-endotoxin in cotton plant. Economic analysis on the influence of new science and technologies from those such as biotechnological products as in the case of the commercialized GM cotton technology has been indicative of the spurt in cotton production success while indicating the possible technology stagnation in the event of pest(s) building up resistance to the plant-expressed Bt delta-endotoxin (Morse et al. 2005, 2012; Chaturvedi et al. 2012). The reliance of GM cotton technology for bollworm tolerance (Kranthi et al. 2000) did not support the aspiration of sustainable cotton production as the oligophagous pink bollworm did become resistant to the endotoxin expressed in the cotton crop (Wu et al. 2008; Tabashnik et al. 2013), as it happened earlier in case of chemical pesticides.

However, the appearance of invasive species of papaya mealybugs and other native mealybug species did make cotton farms suffer severe crop loss during 2010–2013. The mirid bug outbreak in Bt cotton has been reported in China (Lu et al. 2010) and in India (Udikeri et al. 2010a, b). Recent spurt in whitefly population in cotton farms of northern states signalled the breakdown of natural mortality factors of this pest. The evolution of pest management in cotton crop is anticipated to move towards AESA-supported non-chemical pest management tools of cotton IPM tool box. Thus the imperative of IPM with AESA support gains more relevance in GM cotton cultivation instead of over-reliance on the costly modern biotechnological tools alone for crop variety development. The IPM toolbox containing the above-described pest suppression tools shall be suitably adapted for each cotton-growing zone and sustain the technology at hand with the farmers.

11.4 Conclusion

Depredatory insects of cotton crop are destructive to farmers' effort to harvest economic yield from the crop. Recent invasion by a number of invasive pest species, such as mealybugs, throughout cotton-growing states and the whitefly outbreak in northern states indicate the upsets in natural enemy system as well as influence of anthropogenic alterations in the agroecosystem. The GM cotton crop becoming vulnerable to high incidence of pests other than bollworms as well as bollworms tending to tolerate delta-endotoxin expressed in GM cotton are future concerns for farmers and issues for research to find novel cotton varieties that can tolerate the cotton pests and disease. Cotton-based cropping system with mosaic crops, such as pulses, and oilseed crops shall provide better ecosystem for integrated pest management. Non-chemical cotton (organic) production system did flourish in rainfed cotton states to make sure that the cost of cultivation is minimized along with sustained ecological footprint to make cotton farming less invasive into natural niches and process systems.

Acknowledgements We recognize the support provided by various colleague entomologists and professionals and research institutions in sharing information, data and knowledge to make this chapter wholesome.

References

- Abbas G, Arif MJ, Saeed S (2005) Systematic status of a new species of the genus *Phenacoccus* Cockerell (Pseudococcidae), a serious pest of cotton, *Gossypium hirsutum* L., in Pakistan. Pak Entomol 27:83–84
- Almand LK (1995) *Gaucha* seed treatment for protection against early season insects. Miles Inc., Benoit, MS, USA. In: Proceedings Beltwide Cotton conferences 2, pp 1063–1065
- Anonymous (2010) ICAR-CICR. <http://cicr.org.in/Database/dbcottonpest.html>. ICAR-CICR http://cicr.org.in/Database/pest_nat_enemies.html
- Armes NJ, Cooter RJ (1991) Effects of age and mated status on flight potential of *Helicoverpa armigera* (Lepidoptera: Noctuidae). Physiol Entomol 16:131–144
- Arora R, Jindal V, Rathore P, Kumar R, Singh V, Baja L, Atwal AS, Dhaliwal GS (2001) Agricultural pests of South Asia and their management. Kalyani Publishers, New Delhi
- Attique MR, Ahmad Z (1990) Investigation of *Thrips tabaci* Lind. as a cotton pest and the development of strategies for its control in Punjab. Crop Prot 9(6):469–473
- Avidov Z (1956) Bionomics of the tobacco whitefly *Bemisia tabaci* (Genn.) in Israel. Israel Ktawn 7:25–41
- Ayyar TVR (1922) Weevil fauna of South India with special reference to species of economic importance. Bull Agric Res Inst 125:15
- Ayyar TVR (1932) Insects attacking the cotton plant in India. Madras Agric Dep Bull 28:1–28.1
- Bellows TS, Fisher TW (1999) Handbook of biological control: principles and application of biological control, vol 418. Academic, London
- Berlinger MJ, Magal Z, Benzioni A (1983) The importance of pH in food selection by tobacco whitefly, *Bemisia tabaci*. Phytoparasitica 11:151–160
- Bhale NL (1999) Heterosis breeding. In: Sundaram V et al (eds) Handbook of cotton. Indian Society of Cotton Improvement, CIRCOT, Mumbai, pp 57–78, 548 pp
- Bhattacharjee NS, Gupta SL (1972) A new species of *Heliothis* Ochsenheimer (Noctuidae, Lepidoptera) infesting cotton and *tur* (*Cajanus indicus*) in India with observations on the three other common species of the genus. J Nat Hist 6:147–151
- Bournier JP (1994) *Thysanoptera*. In: Mathews GA, Turnstall JP (eds) Insect pests of cotton. CAB International, Surrey, 381–392p
- Bravo A, Gill SS, Soberón M (2007) Mode of action of *Bacillus thuringiensis* Cry and Cyt toxins and their potential for insect control. Toxicon 49(4):423–435
- Broodryk SW, Mathews GA (1994) *Dysdercus* (Hemiptera: Pyrrhocoridae) and other Heteroptera. In: Mathews GA, Tunstall JP (eds) Insect pests of cotton. CAB International, Wallingford, 593p
- Brown AWA (1968) Insecticide resistance comes of age. Bull Entomol Soc Am 14:3–9
- Butani DK (1970) Insect pests of cotton. Western Herbaceum Region of India. Pest Artic News Summ 6(1):56–64
- CABI (2015) Invasive species compendium. <http://www.cabi.org/isc/datasheet/30965>
- Carson R (1962) Silent Spring. M.A. Houghton Mifflin, Boston, 368 pp
- Chaturvedi S, Srinivas KR, Joseph RK, Singh P (2012) Approval of GM crops: socio-economic considerations in developing countries. Econ Pol Wkly XLVII(23):53–61
- Cheema MA, Muzaffar N, Ghani MA (1980) Biology, host range and incidence of parasites of *Pectinophora gossypiella* (Saunders) in Pakistan. Pak Cottons 24:37–73
- Choudhary B, Gaur K (2010) Bt cotton in India: a country profile. ISAAA series of biotech crop profiles. ISAAA, Ithaca

- Cygler M, Borisova S, Grochulski P, Masson L, Pusztai-carey M, Schwartz JL, Brousseau R (1995) *Bacillus thuringiensis* CryIA(a) insecticidal toxin: crystal structure and channel formation. *J Mol Biol* 254(3):447–464
- Dahiya AS, Singh R (1982) Bioefficacy of some systemic insecticides against jassids, thrips and whitefly attacking cotton. *Pesticides* 16:13–14
- Devaiah MC, Govindan R, Thippeswamy C, Rangaswamy HR, Thimmaiah G (1981) External morphology of the cotton shoot weevil, *Aldiodes affaber* Aurivillius (Coleoptera: Curculionidae). *Mysore J Agric Sci* 15:431–438
- Dhandapani N, Kalyanasundaram M, Swamiappan M, Sundarababu PC, Jayaraj S (1992) Experiments on management of major pests of cotton with biological control agents in India. *J Appl Entomol* 114:52–56
- Dhara Jothi B, Surulivelu T, Gopalakrishnan N (2008) Status of mealybug on cotton in various parts of India. In: Proceedings of the national consultation on Mealybug management, pp 8–10. Central Institute for Cotton Research, 28–29 January 2008, Nagpur
- Dobbs RR, Buehring NW, Reed JT, Harrison MP (2006) Thrips control: response to Temik and Gaucho in UNR Cotton. Research Report 23(16), Mississippi State University Department of Entomology and Plant Pathology. <http://msucare.com/pubs/researchreports/rr23no16.pdf>
- Eastop VF, Hill Ris Lambers D (1976) Survey of the World's aphids. W. Junk, The Hague, 533pp
- Elbert A, Overbeck H, Iwaya K, Tsuboi S (1990) Imidachlopid, a novel systemic nitromethylene analogue insecticide for crop protection. In: Proceedings of the British crop protection conference, pest and diseases. BCPC Publication/Thornton Health, Brighton/Surrey, pp 21–28
- Fitt GP (1989) The ecology of *Heliothis* in relation to agroecosystems. *Annu Rev Entomol* 34:17–52
- Fitt GP (1990) Host selection in the Heliothinae. In: Bailey WJ, Ridsdill-Smith TJ (eds) Reproductive behaviour in insects – individuals and populations. Chapman & Hall, London, pp 172–202
- Frisbie RE, El Zik K, Wilson LT (1989) Integrated pest management systems and cotton production. Wiley, New York. 437 pp
- Ghosh D, Pangborn W, Galitsky N, Cody V, Wojtczak A, Luft JR, English L (2001) Structure of the insecticidal bacterial delta-endotoxin, Cry3Bb1 of *Bacillus thuringiensis*. *Acta Crystallogr D* 57(8):1101–1109
- Goyal NP (1974) Heavy population of dusky cotton bug on sunflower. *Indian Bee J* 36:21
- Gutierrez AP, Butler GD, Ellis CK (1981) Pink bollworm diapause induction and termination in relation to fluctuating temperatures and decreasing photophases. *Environ Entomol* 10:936–942
- Hammad SM, Armanius NE, El-Deeb AA (1973) Some biological aspects of *Oxycareus hyalinipennis* Costa. *Bulletin de la Societe Entomologique D'Egypte (RAE)* 56:33–38
- Hardwick DF (1965) The corn earworm complex. *Mem Entomol Soc Can* 40:247
- Hargreaves H (1948) List of recorded cotton insects of the world. Commonwealth Institute of Entomology, London, 50pp
- Hill D (1975) *Spodoptera litura* (F.). In: Agricultural insect pests of the tropics and their control. Cambridge University Press, London
- Hossain SMA, Baqui MA (2010) Effect of Gaucho-fertilizer interaction and agronomic characters on the incidence of pests of smooth and hairy variety of cotton in Bangladesh. *Int J Sustain Crop Prod* 5(4):46–50
- Husain MA, Trehan KN (1933) The life history, bionomics and control of the white fly of cotton (*Bemisia gossypiperida* M & L). *Indian J Agric Sci* 3:701–753
- Ignoffo CM (1981) The fungus, *Nomuraea rileyi* as a microbial insecticide. In: Burges HD (ed) Microbial control of pests and plant diseases of 1970–80. Academic, New York, pp 513–536
- Ingram WR (1981) Pests of West Indian Sea Island cotton. Centre for Overseas Pest Research, London, 35pp. + 90 colour plates
- Ingram WR (1994) *Pectinophora* (Lepidoptera: Gelechiidae). In: Mathews GA, Tunstall JP (eds) Insect pests of cotton. CAB International, London, pp 107–150, 593 pp
- Jayaraj S (1982) Biological and ecological studies of *Heliothis*. In: Reed W, Kumble V (eds) Proceedings of the international workshop on *Heliothis* management. ICRISAT Centre, Pattancheru, pp 17–28

- Jhala RC, Bharpoda TM, Patel MG (2008) *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) – the mealybug species recorded first time on cotton and its alternate host plants in Gujarat, India. *Uttar Pradesh J Zool* 28(3):403–406
- Kenmore P (1997) A perspective on IPM. *LEISA* 13(4):14–15
- Kennedy GG, Nienhuis J, Helentjaris T (1987) Mechanism of arthropod resistance in tomatoes. In: Nevin DJ, Jones RA (eds) *Tomato biotechnology*. Alan R. Liss, New York, pp 145–154
- Khan Q, Rao VP (1960) Insects and mites. In: *Cotton in India: a monograph*, vol 2. Indian Central Cotton Committee, Bombay, pp 217–301, 474 p
- Khan M, Kelly D, Hickman M, Mensah R, Brier H, Wilson L (2004) Mirid bug management in Australian cotton R&D Corporation. November, 2004. <http://thebeatheat.com.au/mirids/mirids-in-mungbean>
- King ABS (1994) *Heliothis/Helicoverpa* (Lepidoptera: Noctuidae). In: Mathews GA, Tunstall JP (eds) *Insect pests of cotton*. CAB International, Wallingford, pp 39–106, 593 p
- Kogan M (1988) Integrated pest management. *Entomol Exp Appl* 49:59–70
- Kogan M (1998) Integrated pest management: historical perspectives and contemporary developments. *Annu Rev Entomol* 43:243–270
- Kranthi KR (2005) Insecticide resistance monitoring, mechanisms and management manual. Central Institute of Cotton Research, Nagpur, 153 p http://www.cicr.org.in/pdf/insecticide_resistance_KRK.pdf
- Kranthi KR (2015) Pink bollworm strikes Bt cotton. *Cotton Statistics and News* 35: 1–6. http://cicr.org.in/pdf/Kranthi_art/Pinkbollworm.pdf
- Kranthi S, Kranthi KR, Lavhe NV (1999) Geographical variation in susceptibility of *Earias vitella* to Cry toxins. *Crop Prot* 18:551–555
- Kranthi KR, Kranthi S, Ali S, Banerjee SK (2000) Resistance to Cry 1Ac in a laboratory selected strain of *Helicoverpa armigera*. *Curr Sci* 78(8):1000–1004
- Leclant F, Deguine JP (1994) Aphids (Hemiptera: Aphididae). In: Mathews GA, Turnstall JP (eds) *Insect pest of cotton*. CAB International, Wallingford, 593 p
- Li JD, Carroll J, Ellar DJ (1991) Crystal structure of insecticidal delta-endotoxin from *Bacillus thuringiensis* at 2.5 Å resolution. *Nature* 353(6347):815–821
- Lopez JD, Shaver TN, Dickerson WA (1990) Population monitoring of *Heliothis* spp. using pheromones. In: Ridgeway RL, Silverstein RM, Inscoc MA (eds) *Behaviour-modifying chemicals for insect management*. Marcel Dcker, New York, pp 473–496
- Lu Y, Wu K, Jiang Y, Xia B, Li P, Feng H, Wyckhuys KA, Guo Y (2010) Mirid bug outbreaks in multiple crops correlated with wide-scale adoption of Bt cotton in China. *Science* 328(5982):1151–1154
- Luttrell RG, Fitt GP, Ramalho FS, Sugoyaeve ES (1994) Cotton pest management: part 1A. Worldwide perspective. *Annu Rev Entomol* 39:527–542
- Mani HC, Krishna SS (1984) Pupal cocoon color of mated males and females influencing reproductive potential in *Earias fabia* (Lepidoptera: Noctuidae). *J Adv Zool* 5:52–54
- Manohar VS, Udikeri SS, Patil SB, Bhat R, Yadahalli KB (2012) Seasonal dynamics of mirid bug (*Creontiades biseratense* Distant) population in Bt cotton in Haveri district of Karnataka. *Karnataka J Agric Sci* 25(2):276–277
- Mathews M (1987) The classification of *Heliothinae* (Noctuidae). Ph.D. thesis, British Museum (NaturalHistory) and King's College, London University, 253 pp
- Mathews GA (1994a) Other Lepidoptera. In: Mathews GA, Tunstall JP (eds) *Insect pests of cotton*. CAB International, Wallingford, pp 215–221, 593 pp
- Mathews GA (1994b) Chemical control. In: Mathews GA, Tunstall JP (eds) *Insect pests of cotton*. CAB International, Wallingford, pp 535–558, 593 pp
- Mathews M (1991) Classification of the *Heliothinae*. *Nat Res Inst Bull* 44:6, 195p
- Melander AL (1914) Can insects become resistant to sprays? *J Econ Entomol* 7:167–172
- Monga D, Kumar R, Pal V, Jat MC (2009) Mealybug a new pest of cotton crop in Haryana: a survey. *J Insect Sci* 22(1):100–103
- Morse S, Bennett RM, Ismael Y (2005) Genetically modified insect resistance in cotton: some farm level economic impacts in India. *Crop Prot* 24(5):433–440

- Morse S, Mannion AM, Evans C (2012) Location, location, location: Presenting the economic evidence regarding genetically modified crops. *Appl Geogr* 34:274–280
- Mound LA, Halsey SH (1978) *Whitefly of the world*. Wiley, Chichester, 340 pp
- Munro JM (1994) Cotton and its production. In: Mathews GA, Tunstall JP (eds) *Insect pests of cotton*. CAB International, London, pp 3–26, 593 pp
- Nagrare VS, Kranthi S, Biradar VK, Zade NN, Sangode V, Kakde G, Shukla RM, Shivare D, Khadi BM, Kranthi KR (2009) Wide spread infestation of the exotic mealybug species, *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae), on cotton in India. *Bull Entomol Res* 99:537–541
- NBAIR (2016) <http://www.nbair.res.in/insectpests/Poppiocapsidea-biseratense.php>
- Nesbitt BF, Beevor PS, Hall DR, Lester R (1979) Female sex pheromone components of the cotton bollworm *Heliothis armigera*. *J Insect Physiol* 25:535–541
- Osgur AF, Sekeroglyu E (1984) Population developments of *Bemisia tabaci* (Genn.) (Homoptera: Aleyrodidae) on various cotton varieties in Cukurova, Turkey. In: XVII international congress of entomology. Abstract volume, p 568
- Parameswaran S, Chelliah S (1984) Damage potential and control of cotton stem weevil, *Pemphorus affinis*. *Trop Manage* 30(2):121–124
- Patel R, Yadav D, Saramma P (1979) Impact of mass releases of *Chelonus heliopa* Gupta and *Telenomus remus* Nixon against *Spodoptera litura* (Fabricius). *J Entomol Res* 3(1):53–56
- Pawar CS, Sithanatham S, Bhatnagar VS, Reed W (1988) The development if sex pheromone trapping of *Heliothis armigera* at ICRISAT, India. *Trop Pest Manage* 34:39–43
- Pearson EO (1958) The insect pests of cotton in tropical Africa. Empire Cotton Growing Corporation and Commonwealth Institute of Entomology, Lodo, pp 74–95
- Piccardi P, Capizza A, Casani G, Spinelli P, Arsura E, Massardo P (1977) A sex pheromone component of the old world bollworm, *Heliothis armigera*. *J Insect Physiol* 23:1443–1445
- Pigott CR, Ellar DJ (2007) Role of receptors in *Bacillus thuringiensis* crystal toxin activity. *Microbiol Mol Biol Rev* 71(2):255–281
- Pradhan S (1946) Insect population studies. IV. Dynamics of temperature effect on insect development. *Proc Nat Insect Sci India* XII(7):385–404
- Prishanthini M, Laxmi VM (2009) The *Phenococcus solenopsis*. Department of Zoology, Eastern University, Sri Lanka. Available at: <http://www.dailynews.lk/2009/07/01/fea30.asp>
- Puri SN, Murthy KS, Sharma OP (1999) Integrated pest management for sustainable cotton production. In: Sundaram V et al (eds) *Handbook of cotton*. Indian Society of Cotton Improvement, CIRCOT, Mumbai, pp 233–245, 548pp
- Rajendran TP, Basu AK (1999) Integrated pest management in cotton – historical perspective, present scenario and future strategies. In: Sundaram V et al (eds) *Handbook of cotton*. Indian Society of Cotton Improvement. CIRCOT, Mumbai, pp 205–232, 548pp
- Rajendran TP, Soth J (1997) A suitable option utilisation of mass-produced bioagents in cotton protection. *Gate (German Appropriate Technology Exchange)* 1/97 (March, 1997) pp 28–30.
- Rajendran TP, Soth J (1999) Organic cotton cultivation in India – an attempt in Maharashtra for no-pesticide crop protection. *J Indian Soc Cotton Improv* 24:45–47
- Rajendran TP, Venugopalan MV, Tarhalkar PP (1999) Organic cotton farming. In: Sundaram V et al (eds) *Handbook of cotton*. Indian Society of Cotton Improvement, CIRCOT, Mumbai, pp 414–427, 548 pp
- Ram P, Chopra NP (1984) Population dynamics of Dusky cotton bug, *Oxycarenus hyalinipennis* Costa on cotton. *Indian J Entomol* 50(2):161–164
- Ramaswamy SB (1990) Periodicity of oviposition, feeding and calling by mated female *Heliothis virescens* in a field cage. *J Insect Behav* 3:417–427
- Reddy AS, Rao NV (1989) Cotton whitefly-a review. *Indian J Plant Prot* 17:171–179
- Reed W (1994) *Earias* spp. In: Mathews GA, Tunstall JP (eds) *Insect pests of cotton*. CAB International, London, pp 151–176, 593 p
- Reed W, Pawar CS (1982) *Heliothis*: a global problem. In: Reed W, Kumble V (eds) *Proceedings of the international workshop on Heliothis management*. ICRISAT Centre, Pattancheru, pp 9–14

- Sadras VO (1995) Compensatory growth in cotton after loss of reproductive organs. *Field Crop Res* 40:1–18
- Santhanam V, Sundaram V (1999) Historical perspectives of cotton in India. In: Sundaram V et al (eds) *Handbook of cotton*. Indian Society of Cotton Improvement, CIRCOT, Mumbai, 548pp
- Sethi BL (1960) History of cotton. In: *Cotton in India: a monograph*, vol I. Indian Central Cotton Committee, Bombay, pp 1–39, 474 p
- Sharma RK, Mueller AJ, Reynolds HT, Hannibal RM (1973) Techniques of trapping pink boll-worm males. *Calif Agric* 27:14–15
- Sikka SM, Joshi AB (1960) (a) Breeding. pp.137–335& (b) Genetics. pp 403–466. In: *Cotton in India: a monograph*, vol I. Indian Central Cotton Committee, Bombay, 474 p
- Sims SB, Greenplate JT, Stone TB, Caprio MA, Gould FL (1996) Monitoring strategies for early detection of Lepidoptera resistance to *Bacillus thuringiensis* insecticidal proteins, pp 229–242
- Singh P, Narayanan SS (1999) Cotton improvement procedures. In: Sundaram V et al (eds) *Handbook of cotton*. Indian Society of Cotton Improvement, CIRCOT, Mumbai, pp 41–56, 548 pp
- Singh VV, Mohan P, Narayanan SS (1999) Cotton genetic resources. In: Sundaram V et al (eds) *Handbook of cotton*. Indian Society of Cotton Improvement, CIRCOT, Mumbai, pp 18–40, 548 pp
- Sithanantham S, Ballal CR, Jalali SK, Bhaktavalsalam N (eds) (2013) *Biological control of insect pest*. Springer India, p 424
- Smith WC, Cothren TJ (1999) Cotton: origin, history, technology, and production. <https://books.google.co.in/books?isbn=0471180459>
- Srinivas M, Patil BV (2004) Seasonal incidence and management of Dusky cotton Bug, *Oxycarenus laetus* Kirby on cotton. *Karnataka J Agric Sci* 17(3):482–486
- Subramanian TR (1959) Biology of *Aldicodes affaber* Aurivillius. *Indian J Agric Sci* 29:81–89
- Sundaramurthy VT, Basu AK (1985) Management of cotton insect pests in polycrop systems in India. *Outlook Agric* 14(2):79–82
- Sundaramurthy VT, Chitra K (1992) Integrated pest management in cotton. *Indian J Pl Prot* 20:1–17
- Sundaramurthy VT, Gururajan KN (1992) Cotton production in India – newer varieties and hybrids make impact on output. *Agricultures Industry*. Vadamalai Publication, Bangalore
- Surulivelu T, Rajendran TP (2003) Cotton Stem weevil management. *The Hindu*, 5 September. <http://www.thehindu.com/seta/2003/09/05/stories/2003090500350300.htm>
- Sweet MH (2000) Seed and chinch bugs. In: Schaefer CW, Panizzi AR (eds) *Heteroptera of economic importance*. CRC Press, Boca Raton, pp 143–264, 828 p
- Tabashnik BE, Brévault T, Carrière Y (2013) Insect resistance to Bt crops: lessons from the first billion acres. *Nat Biotechnol* 31:510–521
- Tarhalkar PP, Venugopalan MV, Rajendran TP, Bambawale OM, Kairon MS (1996) Generation and evaluation of appropriate technology for organic cotton cultivation in rainfed vertisols. *J Indian Soc Cotton Improv* 21:111–122
- Thangavelu K (1978) Population dynamics of the dusky cotton bug, *Oxycarenus laetus* Kirby in relation to climatic variation (Heteroptera: Lygaeidae). *Proc Indian Acad Sci B Anim Sci* 87(12):387–395
- Tinsley JD (1898) Notes on Coccidae, with descriptions of new species. *Can Entomol* 30:317–320
- Udikeri SS, Patil SB, Shaila HM, Guruprasad GS, Patil SS, Kranthi KR, Khadi BM (2010a) Mirid menace-a potential emerging sucking pest problem in cotton. https://www.icac.org/tis/regional_networks/documents/.../udikeri.pdf
- Udikeri SS, Kranthi KR, Patil SB, Modagi SA, Vandal NB (2010b) Bionomics of mirid bug, *Creontiades biseratense* (Distant.) and oviposition pattern in Bt cotton. *Karnataka J Agric Sci* 23:153–156
- Vennila S (2008) Pest management for cotton ecosystem or ecosystem management for cotton protection? *Curr Sci* 94(11):1351–1352

- Vennila S, Deshmukh AJ, Pinjarkar D, Agarwal M, Ramamurthy VV, Joshi S, Kranthi KR, Bambawale OM (2010) Biology of the mealybug, *Phenacoccus solenopsis* on cotton in the laboratory. J Insect Sci 10:115. Available online: insectscience.org/10.115
- Venugopal K, Rajendran TP, Ramamoorthy K, Natarajan K, Khan HH (1996) Organic cotton: present status and future prospects in India. J Indian Soc Cotton Improv 21:105–107
- Vickers J, Baker TC (1992) Male *Heliothis virescens* maintain upwind flight in response to experimentally pulsed filaments of their sex pheromone (Lepidoptera: Noctuidae). J Insect Behav 5(6):669–687
- Vijaykumar NG, Ranjithkumar L, Rajesh Chowdary L (2011) Shoot Weevil (*Alcidodes affaber* Auriv) Infestation in Bt. Cotton Growing Belts of Karnataka. Res J Agric Sci 2(1):160–161
- Waterhouse D (1993) The major arthropod pests of economic significance affecting major crops of the countries in Asia and the Pacific region. Technical Document No. 135. Regional FAO Office for Asia and the Pacific (RAPA), Bangkok, Thailand.
- Watson TF, Johnson PH (1974) Larval stages of the pink bollworm, *Pectinophora gossypiella*. Ann Entomol Soc Am 67:812–814
- Wu K-M, Lu Y-H, Feng H-Q, Jiang Y-Y, Zhao J-Z (2008) Suppression of cotton bollworm in multiple crops in China in areas with Bt toxin-containing cotton. Science 321(5896):1676–1678