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ACKNOWLEDGEMENT. Grant support from DST-SERC for young scientists (NO. SR/FTP/LS-192/2000), New Delhi is acknowledged.

Received 23 May 2003; revised accepted 9 March 2004

The sugarcane woolly aphid, *Ceratovacuna lanigera* Zehntner (Hemiptera: Aphididae): its biology, pest status and control

Sunil Joshi* and C. A. Viraktamath

Department of Entomology, University of Agricultural Sciences, GKVK, Bangalore 560 065, India

Sugarcane woolly aphid, *Ceratovacuna lanigera* Zehntner has been recently reported in outbreak proportions from western and southern India. Though the pest was first reported from West Bengal in 1958 and later from other parts of Northeast India, it had not made its way to other parts of India. The pest breeds on plants of the family Poaceae, but has been also observed on members of Bixaceae, Theaceae and Combretaceae. It has been recorded on ten species of plants in India. It reproduces parthenogenetically and has an anholocyclic (absence of sexually producing generation) life cycle. Thirty-eight natural enemies have been recorded on the aphid from different parts of the world. Recent surveys in the pest-affected areas of Maharashtra (western India) and Karnataka (southern India) have yielded several indigenous predators which include coccinellids, neuropterans, syrphids and a pyralid. Integrated pest management involving mainly mechanical and biological control appears to be the best option. There is ample scope for more directed work on this important emerging pest, especially in the areas of pest ecology and distribution. The role of resistant varieties, and biological, cultural and mechanical control in managing the pest needs to be carefully evaluated.

SUGARCANE is attacked by several aphid species in India. Raychaudhuri[1] listed 17 species of aphids associated with sugarcane of which seven belong to subfamily Aphidinae; five to Pemphiginae; two to Drepanosiphinae and three to Hormaphidinae. Among the three hormaphidine species in the genus *Ceratovacuna* Zehntner, *Ceratovacuna lanigera* Zehntner is a serious pest of sugarcane in several parts of the Oriental region. The species is known from India, Nepal, Bangladesh, East and South Asia, Fiji and Solomon Islands[2] (Table 1). It has been recorded on other members of the family Poaceae like bamboo and

*For correspondence. (e-mail: sunjoshi_pdbc@rediffmail.com)

other grasses. *C. lanigera* lives in large colonies, sucking phloem sap from the leaves and excreting copious honeydew onto foliage leading to the development of sooty mould. The direct and indirect damage affects sugarcane yield and quality. In India, the pest was known only from Northeast India, but recently, it has made its entry into western and southern parts of the country. This article reviews the present status of knowledge on the biology, behaviour, pest status and control strategies of the pest.

Taxonomy and nomenclature

In 1897 Zehntner erected the genus *Ceratovacuna* under the tribe Cerataphidini with *C. lanigera* Zehntner as the type species. The name *C. lanigera* is preferred to *Oregma lanigera* van Deventer (1906) and *Cerataphis sacchari-vora* Matsumura (1917), which are junior synonyms of this species[3]. This genus is characterized by the presence of frontal processes in apterae and alatae. Apterae often possess crenulated margins of wax glands arranged in a row up to the seventh and eighth tergites, with similar wax glands on the lateral margin. Such wax glands are absent in alatae. Head in apterae is fused with prothorax or with entire thorax, and the eighth tergite is always free. Forewings are with media once branched and hindwings with two oblique veins. The species of the genus breed on plants belonging to the families Styracaceae, Poaceae, Arecaceae and Orchidaceae.

Among the 14 species of *Ceratovacuna* known from the world[4], seven occur in the Indian region, viz. *silvestrii* Takahashi, *perglandulosa* Basu, Ghosh and Raychaudhuri, *indica* Ghosh, Pal and Raychaudhuri, *spinulosa* Ghosh and Raychaudhuri, *lanigera* Zehntner, *graminum* van der Goot and *nekoashi* (Sasaki). Among these, *indica*, *perglandulosa* and *spinulosa* are endemic and are known only by apterae viviparae. *C. nekoashi* (Sasaki) is known only from northwest Himalaya[4], species, viz. *silvestrii*, *perglandulosa*, *indica*, *spinulosa*, *lanigera* and *nekoashi* are known from northeast India. Patil[5] reported the presence of *C. graminum* van der Goot in India. The US National Collection of Aphididae records also indicate deposition of a specimen of *C. graminum* van der Goot of Indian origin. However, there is no literature indicating the occurrence and distribution of this species from south or north India. Among all the species known from India, the most commonly distributed species is *C. lanigera*.

Table 1. Geographical distribution of *Ceratovacuna lanigera*[82] and sequence of its appearance in different states of India

Place	Pest status	Year of appearance	Reference
Brunei Darussalam	Minor	1993	84
Fujian	Minor	1927	85
Guangdong	Minor	1928	86
Guangxi	Minor	1945	87
Taiwan	Major	1910	88
Yunnan	Minor	1928	86
Dutch East Indies	Minor	1925	89
Indonesia	Minor	1993	84
Java	Major	1900	90
Kyushu	Minor	1924	91
Ryukyu Archipelago	Major	1971	92
Malaysia	Major	1977	93
Myanmar	Minor	1935	94
Philippines	Major	1917	95
Sri Lanka	Minor	1971	92
Thailand	Minor	1993	84
Vietnam	Major	1928	86
Fiji	Minor	1946	96
Papua New Guinea	Minor	1953	97
Indo-China	Minor	1941	98
India			
West Bengal	Minor	1958	6
Tripura	Minor	1963	99
Assam	Minor	1967	100
Uttar Pradesh	Minor	1971	101
Arunachal Pradesh	Minor	1973	102
Sikkim	Minor	1979	103
Maharashtra	Major	2002	5
Karnataka	Major	2002	104

Present status of the pest in India

The pest was first recorded in West Bengal[6] and later in different parts of Northeast India as a minor pest. In Maharashtra, incidence of *C. lanigera* was recorded for the first time in July 2002 in Sangli district. Later, the infestation spread to Kolhapur, Satara, Pune, Solapur and Ahmednagar. A total of 15.5% of the area under sugarcane is presently infested, with the highest infestation in Sangli (25.29% of total sugarcane area) followed by Kolhapur (21.27% of total area)[7].

In Karnataka, the infestation was first observed in Athani taluk, Belgaum district in September 2002. Subsequently, it was recorded in Raibag, Chikkodi, Hukkeri and Gokak taluks. So far, infestation has been recorded in five districts, viz. Bagalkot, Bijapur, Bellary, Bidar and Belgaum. The highest area of incidence was recorded in Belgaum with 51.55% of total sugarcane area infested, followed by Bagalkot with 31.90%. Incidence in Bidar was the lowest (0.43% of total sugarcane area)[8]. The infestation has now spread to other districts of Karnataka, viz. Koppala, Davangere, Haveri, Shimoga and Raichur (through results of survey conducted by C.A.V.).

Apart from Maharashtra and Karnataka, the woolly aphid has spread to Uttar Pradesh, Andhra Pradesh (pers. commun. RRS, Rudruru and RRS, Vuyyuru), Bihar and Uttaranchal.

Recently, attempts were made to predict the potential geographic spread of the pest by using two computational approaches, viz. GARP and *DIVA*-GIS[9]. The studies indicated that the pest has low probability of spreading to eastern parts of Maharashtra and Andhra Pradesh and is not likely to spread to Tamil Nadu, Kerala and the coastal areas. However, in Karnataka the pest is likely to occur along the transitional belt and in the northern and southern dry zones, but is less likely to occur in south interior Karnataka.

Recent surveys have indicated invasion of the pest in the villages of Vadakali, Lingapura and Anegula, Kekkeri taluk, Mandya district and Doddamalugu, T. Narasipura taluk, Mysore district. Apart from Mandya and Mysore of Karnataka, the pest has recently entered into Tamil Nadu and Kerala also.

Keeping in view the seriousness of sugarcane woolly aphid infestation, the Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India has constituted a central team, which is presently investigating the causes of outbreak, impact of infestation and strategies for control.

Host range

C. lanigera largely feeds on plants of the family Poaceae. There are a few records of the aphid colonizing plants belonging to Bixaceae and Combretaceae (Table 2). In Japan, the species has been recorded on *Miscanthus*, but not on sugarcane[10].

Life cycle and biology

The aphid undergoes an anholocyclic life cycle on Poaceae. In Japan, Kurosu and Aoki[11] found many alatae sexuparae in the laboratory colony on sugarcane and stated that sexuparae played no significant role as they were nonfunctional. No host alternation has been reported in Japan. Takahashi[3] reported host alternating life cycle from *Saccharum* to *Miscanthus* by transfer experiments in Taiwan, even though no sexuals were noted in nature. He studied the biology and found that the nymphal stage occupied ten days and alatae about 14 days.

In Taiwan[12], the optimum temperature for aphid development ranged from 20 to 23°C and aphids became inactive at temperatures below 15°C and above 28°C. The nymphal developmental period varies under different temperature and photoperiod regimes. Apterous nymphal stages occupied ten days[3]; 23–32 days[12] in Japan and 15.8–16.5 days[13] in Taiwan. Alatae, nymphal stage occupied 14 days[3] and 32–40 days[14]. The average longevity of apterous and alatae adults was 36 and 8.3 days[12], 20.5 and 24.1 days[13]. Average fecundity of apterous adult was 60 aphids, while it was 10 aphids in alatae[12]. The rate of reproduction under laboratory conditions varied from 3 to 5 nymphs per day, with total fecundity of 41 to 56.6 aphids[13].

In Philippines, sugarcane varieties were found to influence the life span and number of progeny produced by the aphid[15]. Longer nymphal duration and lower fecundity were recorded on resistant varieties[16].

Behaviour

Sterile, self-sacrificing nymphs referred to as ‘Samurai’ aphids[17], are seen amongst species of Hormaphidinae and in this species also. They have tough and stout body, thickened forelegs and well-developed horns, giving them a pseudoscorpion-like appearance. Certain percentage (20–25) of first instar nymphs of *C. lanigera* attacked eggs and larvae of predaceous syrphid, *Eupeodes* and eggs of chrysopid, *Chrysoperla pallens* Rambur[18].

C. lanigera secretes droplets containing alarm pheromone from cornicles when attacked by the predator, *Pseudoscymnus kurohime* (Miyatake). The number of aphids producing droplets differs based on the stage of the predator that attacks. When attacked by adults, 82% of *C. lanigera* secreted droplets, whereas during larval attack, only 7.2–12% secreted droplets[19].

Seasonal occurrence

Population changes in relation to weather parameters, time of planting and ratooning have been investigated for this pest.

An early rainy season was the major cause for attack during the succeeding year in Indonesia[20], and dry season with high humidity was also conducive for aphid infestation[21]. Long periods of dry and wet seasons inhibited aphid population and alternating rainy and hot days enhanced population growth[20,21]. Severe damage occurred during high temperature and less precipitation in Taiwan[22], whereas dry season was favourable in the Philippines[23].

Table 2. Host plants of *C. lanigera* recorded from India

Host plant	Family	Reference
Bambusa arundinaceae Retz.	Poaceae	105
Bambusa sp.	Poaceae	103, 106
Cynodon dactylon (L.) Pers.	Poaceae	107
Grassum sp.	Poaceae	108
Oplismenus sp.	Poaceae	103
Saccharum officinarum Linnaeus	Poaceae[34,38–41]	6, 101, 102, 105, 109–112
Themeda sp.	Theaceae	113
Unidentified species	Poaceae	112–114
Xylosma longifolia	Bixaceae	113
Unidentified species	Combretaceae	110, 115

Table 3. Natural enemies of *C. lanigera* Zehntner

Natural enemy	Location	References
Parasitoids		
Hymenoptera		
Aphelinidae		
Aphelinus desantisi Hayat	India	35
Encarsia flavoscutellum Zehntner	Java	39
	Taiwan	41
	Netherlands	45
	Philippines	116
	Malaysia	93
	India	35
Braconidae		
Diaeretiella rapae M'Intosh	India	35
Diaeretus oregmae Gahan	Philippines	36
	Taiwan	37
Aphidius sp.	Philippines	15
Encyrtidae		
Anagyrus sp.	India	35
Chalcididae		
Antocephalus sp.	India	35
Predators		
Coleoptera		
Coccinellidae		
Anisolemnia dilatata (Fabricius)	China	49
Cheilomenes sexmaculata (Fabricius)	Philippines	15
	India	77
Coccinella septempunctata Linnaeus	India	61
Coelophora biplagiata (Swartz)	Vietnam	52
	China	117
Coelophora saucia Mulsant	Formosa	12
Cryptogonus orbiculus (Gyllenhal)	Philippines	48
Curinus coeruleus Mulsant	Philippines	118
Harmonia octomaculata (Fabricius)	India	77
Pseudoscymnus kurohime (Miyatake)	Japan	57
Scymnus sp.	Philippines	15
Synonycha grandis (Thunberg)	Philippines	33
	China	49
	Japan	50
	Taiwan	14
	Indo-China	52
Lepidoptera		
Lycaenidae		
Taraka hamada (Druce)	China	119
Pyralidae		
Dipha aphidivora (Meyrick)	Malaysia	120
	China	59
	India	35
	Taiwan	24
	Japan	25
Thiallela sp.	Philippines	15
Diptera		
Syrphidae		
Dideopsis aegrota (Fabricius)	Philippines	15
	India	77
Episyrphus balteatus (De Geer)	India	77
Eupeodes confrater (Wiedemann)	India	35
Eupeodes corollae (Fabricius)	Philippines	15
Eupeodes kuroiwae (Matsumura)	Japan	25
Ischiodon scutellaris (Fabricius)	India	77
Syrphus sp.	Taiwan	24
Neuroptera		
Chrysopidae		
Chrysopa sp.	India	35
Chrysoperla carnea (Stephens)	Philippines	33
Chrysoperla furcifera (Okamoto)	Japan	92
Chrysopa pallens Rambur	Philippines	33
	Japan	18
Dichochrysa alcestes (Banks)	Japan	92
Italochrysa acqualis (Walker)	Japan	92
Hemerobiidae		
Micromus sauteri Esben–Petersen	Philippines	15
	Taiwan	24
	Japan	25
Micromus sp.	India	78
Micromus timidus Hagen	Japan	25
Hemiptera		
Anthocoridae		
Orius persequens (White)	Java	78
Araneae		
Unidentified spiders	Philippines	15
Pathogens		
Aspergillus sp.	Philippines	15
Fusarium moniliforme Sheld.	China	121
Penicillium oxallicum Currie & Thom.	China	121

Autumn-planted canes were more prone to heavy infestation by the aphid in Taiwan[24], while in Japan it was summer-planted canes that were prone to attack[25]. Contrary to the general observation of heavy infestation of sucking pests on ratoon crop, the woolly aphid was less abundant on ratooned sugarcane. The colonies started developing in November and December and then gradually increased during winter, with phenomenal increase during summer.

Attempts were also made in Taiwan to relate time of planting with infestation levels by comparing the length of aphid colony in spring- and autumn-planted crop[26]. The length of the colony developing on autumn-planted cane was higher compared to spring-planted cane. Measurements of the colony increased with decrease in temperature from December to February.

Apterae were observed immediately after germination and infestation increased until the minimum temperature reached 23°C in January-planted canes in Taiwan. The population peaked between the second half of April and the second half of June. Heavy precipitation coupled with high temperatures were the factors causing decline in the aphid population. In addition, typhoons before May were detrimental to the aphid[27].

In Assam, the aphid incidence started in June and increased gradually to reach a maximum of 90.32% in September[28] and declined by January. In Uttar Pradesh, the pest occurred during October to March[29].

The aphid emerged before sunset and continued to emerge until early morning[30]. This probably helped aphids to escape desiccation due to high day temperatures. The spread of the aphid from one field to another thus took place mainly due to wind. Peak take-off occurred just after sunrise, one day after emergence. Wind velocity of more than 6 cm/s increased the number of aphids alighting on the plant.

Mature leaves were more prone to aphid attack compared to young leaves[23]. Takano[14] observed that narrow and erect leaves were affected to a great extent while Patil[5] found that soft, broad and drooping leaves were more suitable for aphid build-up.

Cell-sap concentration was a major factor in inducing susceptibility in different cane varieties[31]. Varieties with low concentration of cell sap (averaging about 4.5° Brix) had lower infestation compared to those with high cell-sap concentration (5.9° Brix). Susceptible varieties were attacked less during rainy season due to drop in cell-sap concentration, which was around 2 to 2.7° Brix[32]. Irrigated fields suffered less infestation because of lower sap concentration. Healthy canes and fertile soil also contributed to the pest status.

Nature of damage

Initial aphid infestation was seen on the under surface of leaves along the midrib and then over the entire under surface, covering it with flocculent, waxy secretion. Copious honeydew excretion often covers the entire upper surface of the leaves, leading to growth of sooty mould[4]. Due to continuous sap-sucking, the crop becomes stunted[33], and continuous infestation leads to reduction in the length, circumference, weight and sugar content of the stalk, and in susceptible varieties in Vietnam[34], loss in tonnage as well as sugar recovery[35]. Gupta and Goswami[28] assessed the effect of 25 and 100% aphid-infested leaves on some yield and quality parameters of sugarcane and found that 100% infestation had detrimental effects on the length (11.6% reduction), girth (3.5% reduction), weight (16.6% reduction), length of internode (18.4% reduction) and width of leaf (4.9% reduction). Juice quality parameters also exhibited considerable reduction. The per cent reduction in sucrose, brix, glucose, purity and commercial cane sugar (CSS) was 53.3, 32.3, 25.3, 31.7 and 64.0 respectively. Preliminary studies on loss estimation being conducted at University of Agricultural Sciences, Dharwad indicate adverse effects of aphid infestation on yield and quality parameters[8].

Ant association

C. lanigera is attended by five species of ants and *Polyrhachis dives* Smith was the most abundant[15]. In addition to removing honeydew, the ant also protects the aphid from natural enemies.

Natural enemies

Seven species of parasitoids, 30 species of predators and three species of fungal pathogens have been recorded on *C. lanigera* (Table 3). Only in recent years, use of some of these natural enemies for management of the pest has been attempted.

Parasitoids

Initial attempts to identify and exploit parasitoids were made as early as 1927. *Encarsia flavoscutellum* Zehntner and *Diaeretus oregmae* Gahan were recorded from Java and Philippines respectively. *D. oregmae* was described by Gahan[36] in Ohio. Stary and Schlinger[37] mentioned the occurrence of the species from Taiwan. Among the two parasitoids, *E. flavoscutellum* caused a natural parasitism of up to 30% in Java. Hazelhoff[38] reported that there was no need for adopting control measures as the parasitoid was prevalent even at early stage of aphid infestation. Techniques to enhance parasitization were outlined by Hazelhoff[39], as he found that even during heavy aphid infestation, the parasitism reached a maximum of 20% only. High humidity was necessary for effective multiplication of the parasitoid[40].

The parasitoids emerged in the early morning and their longevity was reported to be 4–5 days. Females were more abundant than males. Each female laid 1–6 eggs with an average of 2 in a single host. The egg, larval and pupal stages lasted for 2–4, 5–10 and 6–11 days respectively[41].

Hazelhoff[42] developed a sampling method to determine per cent parasitism. He also emphasized the need for redistribution of the parasitoid from old to new plantations, as the parasitoid is a poor flyer[40]. The system of crop rotation is associated with the problem of forced migration of the parasitoid. Subsequent to the publication of notes on utilization of the parasitoid in the field by Hazelhoff[43,44], the parasitoid was evaluated in the field in the Netherlands Indies[45]; however results of this trial are not known.

The parasitoid was introduced into Taiwan[46] and Philippines[23], but it failed to establish owing to the short lifespan of the adult[47] and heavy mortality of the adults during transit[48]. Though the parasitoid has been recorded in India[35], no studies have been made on its multiplication and field evaluation.

Predators

Synonycha grandis (Thunberg) and Anisolemnia dilatata (Fabricius)

S. grandis was recorded as a potential predator of sugarcane woolly aphid in Philippines[33], China[49], Japan[50], Formosa[51] and Indo-China[52]. *S. grandis* and *A. dilatata* have also been reported to feed on the bamboo aphid, *Pseudoregma bambusicola* Takahashi[53].

Liu[49] discussed the geographical distribution and rearing techniques of both the coccinellids that prey on *C. lanigera*. The optimum conditions for rearing were 26°C and 85% RH. The incubation, larval and pupal periods averaged 4, 13.52 and 4.23 days respectively, for *S. grandis*. The corresponding values for *A. dilatata* were 4, 13.16 and 5.16 respectively. Adult *A. dilatata* consumed on an average 87.8 aphids in an hour, the first instar larva, 100 aphids per day and grown up larva, 400–500 aphids per day. *S. grandis* exhibited a little higher feeding potential. Oviposition took place several days after pairing in both coccinellids. *S. grandis* preferred to oviposit on both surfaces of the leaf, and *A. dilatata* was found to lay eggs on thin branches of bamboo. Pupation occurred on leaves. Pupae were the weakest stage in the life cycle and the prepupal stage was parasitized by an unknown chalcid[49].

S. grandis had 11 generations a year. The adult lived for 30–70 days in summer and 60–90 days in winter, and up to six months when the sexes were separated[51]. Premating period varied from 3 to 7 days, whereas preoviposition period was 5–16 days. The oviposition period lasted 1–2 months. The average fecundity was 673 eggs/female. Eggs were laid in masses of about 27. The optimum temperature for egg-hatching ranged from 19 to

22°C. Adult predators reared on agar solution and wheat flour could not oviposit. Biological studies of this predator were also conducted in Japan[50] and India[4] using *C. lanigera* and *C. silvestri* respectively, as hosts.

C. lanigera is most abundant on sugarcane from October to May, but the coccinellid appeared only after December, and was most abundant at the end of May[51].

Owing to difficulty in supplying sufficient aphids as food, attempts were made to rear coccinellids on artificial diets like 10% molasses, molasses with egg yolk, milk powder and few drops of tomato juice[54], but these diets failed. Coccinellids could be reared on aphids during spring, though only 21% of the eggs hatched. In summer, rearing on aphids was not possible perhaps because of high temperature, when adult mortality was high and eggs failed to hatch[54].

Field-released adults (at the rate of 500 per 200 m^2) tended to migrate and only half of them were recovered 20 days after release. The beetles disappeared two months after release, without significantly reducing the aphid population[54].

Though the initial trials with *S. grandis* failed, research on its colonization and utilization was continued in China. Chen *et al.*[55] mass-produced *S. grandis* on field-collected woolly aphids and released them in the field. Takano and Noda[51] suggested cold storage of adults and liberation at the outbreak centres at the right stage of aphid infestation. Deng *et al.*[56] were able to store beetles at low temperature and release them at appropriate levels of infestation. However, in these studies, released beetles could not bring about significant reduction in aphid population.

Successful suppression of the woolly aphid by field release of *S. grandis* was demonstrated by Deng *et al.*[56] after seven years of research. They collected *S. grandis* and *Coelophora biplagiata* Swartz from sugarcane fields and stored them in the laboratory at temperatures ranging from 18 to 20°C and 75–85% RH. A total of 62.96 to 82.9% adult *S. grandis* survived after five months of storage. Survival rate was higher in *C. biplagiata* (45.7 to 100%). A total of 44,660 beetles were released into sugarcane fields, resulting in 90 to 96.6% reduction in aphid population[56].

Species of Coelophora

C. biplagiata was introduced from Indo-China to Taiwan, where it established successfully. Later, it was taken from Taiwan and released in Java[52] in 1925. Similarly, *Coelophora saucia* Mulsant was introduced to Taiwan from Tonkin and it established in the southern parts after initial release[12]. Information on its role in suppressing the population of woolly aphid is not available.

Pseudoscymnus kurohime (Miyatake)

The adults and first to third instar larvae of *P. kurohime* preferred to feed on the first instar nymphs of woolly aphid. However, the fourth instar larvae fed on all stages of the aphid. The larvae attacked the nymphs from the underside of the head and thorax, whereas the adults attacked the abdomen of the prey[57]. However, no evaluation on its potential as a biocontrol agent has been made.

Dipha aphidivora Meyrick

Surveys conducted in China from 1974 to 1984 indicated *D. aphidivora* to be one of the most abundant and important aphid-suppressing factors[27]. The predator has been recorded under three names, *Isauria aphidivora*, *Conobathra aphidivora* and *Cryptoblabes aphidivora* from China, Malaysia and Philippines. Arakaki and Yoshiyasu[58] compared the morphology of the pyralid predators recorded on aphids to resolve the confusion in their identification. Crossing experiments and detailed studies on morphology indicated that all the species were conspecific and a new genus *Dipha* was proposed for this species.

The predator has also been recorded from Dimapur (Nagaland)[35]. Though it was recorded as a predator on woolly aphid during 1978, serious efforts to multiply and use it for biological control were made only in 1997. Chen *et al.*[59] reared the pyralid at 25°C under laboratory conditions using freezed aphid nymphs stored at 1 and – 20°C.

Pathogens

Fusarium moniliforme Sheld. and *Penicillium oxalicum* Currie and Thom. have been recorded as fungal pathogens of *C. lanigera* in China[60]. Lingappa[61] evaluated some entomopathogenic fungi against the aphid and found *Metarhizium anisopliae* to be effective in preliminary studies. Recent field trials conducted at Arabhavi, Karnataka with oil-in-water emulsion of *B. bassiana* and *M. anisopliae* caused 19.84 and 42.26% mycosis respectively[62].

Defensive behaviour of predators

Aphids with aggressive behaviour are known in Hormaphidinae and Pemphiginae and 15 species of aphids have been recorded to be aggressive towards the predators[62]. *C. lanigera* and *C. japonica* (Takahashi) are known to attack immature stages of syrphids, chrysopids and coccinellids[18].

Predators have also evolved strategies to protect themselves from aggressive aphids. Larvae and adults of *S. grandis* and *A. dilatata* are known to exude a toxic chemical (reflex bleeding) from the femoro-tibial joints to protect themselves from soldiers of *C. lanigera*[49]. In addition, both these predators frequently deposit their eggs away from the aphid colony to prevent attack by the aphid soldiers[63].

P. kurohime exhibits a typical egg-protection behaviour[64]. This predator lays eggs on the undersurface of leaves near the leaf midrib in aphid colonies. The eggs are then covered with faeces-like secretion mixed with undigested claws of the prey aphids. This behaviour not only protects the eggs from soldiers, but also protects it from high temperature and cannibalism.

D. aphidivora spins a web around itself and feeds from within this silken tunnel created for defence. The soldiers of *C. lanigera* get entangled in the web and fail to attack the predator[63].

Chemical control

A great deal of laboratory and field research on insecticidal control of *C. lanigera* has been conducted in China, Philippines and Taiwan. Lopez[33] reported that spraying with a contact pesticide, creoline was effective in controlling the woolly. Sprays with 1% camphor oil, yam and bean oil, tea seed oil, tea decoction emulsified with sodium oleate and leaf extract of tobacco were also recommended[65]. Tea seed oil was the most effective treatment, providing 93–99% mortality[66].

Schradan, dematon[67] and low-volume sprays with malathion[68] were recommended in Taiwan and Philippines. Pan and Yang[69] advocated aerial application of methyl demeton and dimethoate. Liu *et al.*[70] also advocated application of dimethoate after June to control *C. lanigera*, without harming natural enemies. Fogging with a mixture of diazinon 60 EC and petrol at ratios of 2 : 3 and 1 : 2 was effective, particularly when carried out on bright, windless days in the afternoon or evening in Indonesia[21]. In China, carbophos 40 EC resulted in more than 95% mortality of *C. lanigera*[71].

For the control of recent outbreaks in Maharashtra and Karnataka, chemicals such as endosulfan, phosalone, monocrotophos, dimethoate and metasystox sprays, and acephate and methyl parathion dust have been recommended[5,61].

Host–plant resistance

Attempts have been made to identify resistant sources in sugarcane germplasm. Pan *et al.*[16] studied the biology and densities of aphid colonies on different varieties and identified the variety ROC 1 to offer resistance to some extent. Similar efforts were made in Indonesia and a resistance breeding programme was started for *C. lanigera*[72]. Two hydroxamic acids, DIBOA and DIMBOA were detected in sugarcane that may contribute to resistance to the aphid, as they do to aphids on cereals[73].

Mechanical control

Patil[5] advocated stripping of infested leaves and burning them to avoid further spread. Such type of mechanical methods have been tried against sucking pests of sugarcane like *Pyrilla perpusilla* (Walker) and have proved successful[74]. Richards[75] pointed out that stripping had other advantages like increase in sugar content as well as germination of seed sets. Gupta[76], however, showed that stripping has disadvantages, such as high cost and mechanical damage to eye buds by mammalian pests and field workers, together with greater level of lodging. Thus, mechanical methods should be followed only after proper evaluation of the costs and benefits of the technique.

Pest control strategies and future prospects

The predictions of potential distribution of the invasive pests are helpful in developing strategies for monitoring and managing serious pests. Recently, attempts have been made to predict the spread of sugarcane woolly aphid. The results of these studies will be useful to fight the pest in an ecologically and economically sound manner[9].

Deng *et al.*[56] and Rabindra *et al.*[77] advocated biological methods by augmentation of the coccinellids, *S. grandis* and *A. dilatata*. The proposed methods are logical, as indiscriminate use of pesticides may lead to outbreak of secondary sucking pests. However, the methods need to be justified economically, as mass multiplication techniques for both coccinellids are yet to be developed. Collection of predatory beetles from different locations and distribution where required is time-consuming as well as labour-intensive. In addition, predatory beetles are highly mobile. Earlier studies have indicated escape of predators from the colonized areas in spite of availability of the host[54]. The other predator that is being proposed to be utilized in India is the pyralid, *D.? aphidivora*[77]. Correct identity of this predator needs to be established and efforts should be made to mass multiply it in the laboratory, conserve it *in situ* in the field and also redistribute it to new areas of infestation. *Micromus* sp. is quite abundant and appears to be a potential candidate for mass multiplication and release[78]. This occurs even under low pest population feeding on first and second instars of aphid. Combination of *Micromus* sp. at low pest population and *D.? aphidivora* at higher population levels may work well in the field.

Parasitoids being more specific compared to predators, are better candidates as biocontrol agents of sedentary species[79] such as *C. lanigera*. Concerted efforts need to be made to explore the parasitoids of this species, such as *E. flavoscutellum* in Northeast India; develop mass rearing techniques; assess their efficacy in the field and develop field-release and conservation strategies.

The recommendations by Patil[5] and Patil *et al.*[80] include proper sanitation, avoidance of transport of infested leaves from one area to another, removal of other alternate hosts in the vicinity, removal of infested leaves by employing labourers, avoiding lodging of canes, burning of trash after harvest and avoiding use of canes from infested fields for sowing. These are general but important recommendations. The suggestion of ploughing after harvest seems baseless, as the pest neither overwinters nor lays eggs in the stubble. Recommendation of release of *Chrysoperla carnea* at the rate of 2500 larvae/hectare[81] is not based on any systematic studies on the performance of the predator against this pest in the field. *C. carnea* can be mass-produced easily and cheaply[80], but the predator has not been successful in suppressing *C. lanigera*[82] and hence it is unlikely to contribute much to its management.

Sprays of the entomopathogenic fungus *M. anisopliae* are being recommended and are also proving effective[61,62]. These recommendations make sense as many pathogenic fungi have performed well in the sugarcane ecosystem[83], being an annual crop with high humidity within the crop canopy, facilitating propagation and rapid spread of fungi. *M. anisopliae* can be easily multiplied on artificial media. Large-scale assessment of this pathogen on the pest is the need of the hour.

There is ample scope for more directed work on this important emerging pest, especially in the areas of host–plant resistance and biocontrol with emphasis on conservation and enhancement of indigenous natural enemies. IPM practices involving habitat management, spacing, irrigation, nitrogen fertilization, resistant varieties, traps, natural enemies, sanitation (removal of older leaves and burning of trash), use of pathogens and safe chemicals need to be developed. There is need to study and analyse important aspects of the pest ecology, so that key mortality factors and density-dependent, potential population-regulating factors of the pest can be exploited. A rigorous experimental evaluation of the potential of biocontrol agents and integration of the best of these control measures in large-scale experiments across locations are required.

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ACKNOWLEDGEMENTS. We thank Dr Samiran Chakrabarti, Department of Zoology, University of Kalyani, Kalyani for confirming the identity of the sugarcane woolly aphid. We also thank Dr R. Muniappan, Agricultural Experiment Station, University of Guam, Mangilao, USA, Dr S. Ramani and Dr J. Poorani, Project Directorate of Biological Control, Bangalore for going through the manuscript and making valuable suggestions. Ms S. K. Rajeshwari, Ms C. A. Shobitha, Mr A. R. Prasanna, Mr S. B. Kongwad and Mr C. B. Kedanuri translated various popular articles in Kannada on this topic. The study leave granted to the S.J. by the Project Director, Project Directorate of Biological Control (ICAR), Hebbal, Bangalore is acknowledged.

Received 30 September 2003; revised accepted 5 March 2004