Role of Parasitoids and Predators in the Management of Insect Pests

Chandish R. Ballal and Abraham Verghese

Abstract

With increasing hazards due to chemical/synthetic pesticides, the only answer to mitigate these ill-effects is use of safe alternatives. Amongst them, use of natural enemies comprising of parasitoids, predators, entomopathogens, etc. as biological control agents is the most effective, environmentally sound and cost-effective pest management approach to control insect pests. It is anticipated that biological control will play an increasingly important role in integrated pest management (IPM) programs as broad-spectrum pesticide use continues to decline. Moreover, biological control is a cornerstone of organic farming, and the production of organic commodities in developed countries like the USA continues to increase at roughly 20% per year (USDA-ERS 2002). Organic farming is no longer considered a cottage industry since retail sales hit $ 14.6 billion in 2006. For a given arthropod pest or weed, a pool of natural enemies often exists which consists of vertebrates, invertebrates and microorganisms. The fundamental problem in applied biological control is to select an appropriate species or combination of species from this pool that will bring about the desired level of pest suppression with minimal impact on non-target species.

Keywords

Predators · Parasitoids · Entomopathogens

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Introduction

Integrated Pest Management (IPM) programs based largely on biological control are of great benefit to agriculture, the quality of rural life and the consumer. Reductions in insecticide, acaricide and herbicide applications should allow farmers

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to reduce production costs and make adjustments for a more sustainable agriculture. Reduced pesticide use will enhance the quality of rural life by decreasing ground and surface water contamination, reducing effects on non-target species (including wildlife) and increasing safety of farm workers and other rural residents. These benefits also accrue at the interface of urban and agricultural environments, where there is an increasing opposition to pesticide use by stakeholders. The reduction in pesticide residues in food is also desirable, although controversy remains over the extent and public health significance of such residues. Background information and justification: Despite many advances in recent years, our practical and conceptual understanding of success and failure in applied biological control fall short of meeting certain current and future requirements. For example, in classical biological control, the rate of establishment of natural enemies is relatively low in the case of arthropod pests (ca. 34 %) (Kimberling 2004); further research into the genetics and ecology of colonization is clearly warranted. In the future, classical biological control should ideally be able to predict (1) the appropriate species (or biotype) or combination of species (and/or biotypes) to release for control of a target pest in a given situation; and (2) the environmental impact resulting from the introduction of an exotic enemy. Non-target impacts to plants or insects from bio-control agents are of great concern to conservation biologists, environmentalists and federal agencies.

More than one-and-half million insect species occur in this world, out of which only about 15,000 (1.0 %) have attained the status of pests while the others, many of which have pestilent potential, remain at low levels. One of the major reasons for the secondary status of such insects is the perpetual regulatory action exerted on them by their natural enemies. This in itself reflects the great potential of biological control, which can be exploited for management of some of our major pests, diseases and weeds by restoring the natural balance through purposeful human intervention. Such an approach could be classical biological control for invasive species, or generally by augmentation or conservation for indigenous pests.

A worldwide review reveals that there have been altogether 120 successful cases of classical biological control of insect pests of which 42 have been completely controlled, 40 substantially controlled and 30 partially controlled. These include pests, diseases and weeds. There are also a number of successful cases by augmentation of natural enemies in several countries. India is rated as one of the top 10 countries in the world in the area of biological control.

In India, innumerable attempts have been made to augment the populations of promising indigenous natural enemies like trichogrammatids, bethylids, chrysopids, ladybird beetles, nuclear polyhedrosis viruses, etc. to control pests of sugarcane, cotton, coconut, coffee, grapevine, tomato, sunflower, etc. To support such augmentative programmes, mass-production of natural enemies is a necessity. Thus, commercial production of biocontrol agents has a great potential which has already received considerable attention in recent years.

Where success has been achieved in classical biological control, the underlying ecological mechanisms are not always clear. After 100 years of effort, we still do not fully understand the mechanisms by which a successful natural enemy operates in nature, or why a particular organism is successful in one situation and unsuccessful in another. Basic research in augmentation and conservation of natural enemies is also needed. In augmentation, we urgently need a coherent theory of inundative/inoculative release as well as basic efficacy data in order to more readily incorporate commercially available predators and parasitoids of arthropod pests into IPM systems. The genetics of mass production must be evaluated experimentally so that quality control procedures can become a regular practice in the commercial production of natural enemies. Advances in the nutrition of parasitoids and predators are needed. Continued commitment to conservation of natural enemies is required, including innovative ways of integrating pesticides and cultural controls with key natural enemy species. Global warming has now been accepted as a serious threat to our natural and agroecosytems. It will be imperative that biological control scientists watch for the effects of climate change on arthropod pests that have been kept in check by natural enemies. Products of biotechnology designed for pest control must also be assessed and incorporated (where appropriate) into IPM programs. In the past five years, scientists have examined interactions between transgenic crops and biological control species, and these studies will increase as more such crops are approved. Finally, biological control scientists are providing management professionals with the sustainable and effective tools with which to manage the relentless pressure of invasive species on natural and agricultural ecosystems.

Exotic pests continue to arrive and many of these will become permanently established. For such pests, the use of classical biological control should remain a high priority. At the same time, our IPM programs must be continuously evaluated, refined and adjusted in response to changes in newer and more specific control technologies and production practices.

Transcending the coordination and cooperation on a given pest is an important shared need for advances in regulatory policy, general methodologies for release and evaluation of natural enemies, and the need to develop sound ecological theory concerning pest population dynamics, predator–prey interactions, and the genetics of colonization in biological control. The advancement in agricultural technology has brought about remarkable changes in the agricultural sector. These changes have been accompanied by excessive use of pesticides. Worldwide, there are 500 species of resistant insects, mites and ticks compared with only 25 in 1955, coupled with this has been the well-publicized environmental effects, such as toxic residues on produce, destruction of beneficial insects and other non-target organisms, and human poisoning. The World Health Organisation (WHO) estimates that worldwide over a million people are poisoned with pesticides each year and up to 2 % of cases may prove fatal. At this juncture, biopesticides offer an alternative method of control that do not seem to provide the rapid development of resistance in the field, leave little, or no toxic residues and are generally harmless to beneficial insects and other non-target organisms.

Parasitoids and predators can be conserved, preserved and multiplied under laboratory conditions or in commercial production units for field release against target pests or diseases. A major benefit in the use of biopesticides is that they are safe for use by human beings and there are no reports regarding hazards caused due to the use of bio-pesticides, while there are innumerable instances on poisoning due to or non-target effects of chemical pesticides.

Developing countries would be highly benefited through development, exploitation and use of parasitoids and predators. The production, sale and use of biopesticides in a developing country can provide local employment opportunities, reduce health risks and costs due to chemical poisoning and environmental damage, improve export earnings through reducing chemical residue levels on export commodities; and in addition to this there are the benefits obtained through the extra control achieved by preserving natural enemies in crop systems and by maintaining indigenous biodiversity.

Biointensive pest management modules have been developed by the Project Directorate of Biological Control (PDBC) (now NBAIR) for management of pests on cotton, sugarcane, rice, citrus and several other crops (Singh 1996; Rabindra and Ballal 2002). These modules lay emphasis on release of biocontrol agents like parasitoids, predators and pathogens and reducing chemical pesticide applications to the possible extent. The pre-requisite of any biocontrol programme is to have a large-scale supply of beneficial agents. Today, in our country, there is a great demand for biocontrol agents, but the major problem is with respect to availability of good quality bioagents at the required place and time.

In India, several parasitoids and predators have been identified, evaluated and recommended for field releases against agricultural pests (Singh 2001). Technologies are available for the production and use of parasitoids and predators (Rabindra et al. 2003; Singh 2002). There are several success stories in the field of biosuppression of crop pests in our country

(Singh 1996). Biological control has gained maximum acceptance amongst sugarcane farmers of India through use of *Trichogramma* species

Biological control is now considered as the most important component of an integrated pest management strategy and typically involves an active human role. Predators, parasitoids and pathogens are utilized in biological control attempts against insect pests and in this chapter we deal with the utility of parasitoids and predators in biological control. Parasitoids have been used in biological control more than any other type of agent. A successful parasitoid should have a high reproductive rate, good searching ability, host-specificity, be adaptable to different environmental conditions and be synchronized with its target host (pest). No parasitoid has all these attributes, but the search should be for one with several of the above characteristics. Parasitoids are generally utilized in three overlapping types of biological control: conservation, classical biological control (introduction of natural enemies to a new locale) and augmentation. Conservation of natural enemies is probably the most important, readily available, generally simple and cost-effective. The role played by natural enemies in nature becomes evident when insecticide use is stopped or reduced. To tackle exotic pests (at times even native pests), we may have to turn to classical biological control. Unfortunately, classical biological control does not always work, the reasons for failure may include the release of too few individuals, poor adaptation of the natural enemy to environmental conditions at the release location and lack of synchrony between the life cycle of the natural enemy and the pest. The third type of biological control involves the supplemental release of natural enemies which could be inoculative (relatively few natural enemies released at a critical time of the season) or inundative (millions may be released). Habitat manipulation could be a useful approach, wherein the cropping system may be modified to favour or augment the natural enemies. Now potential parasitoids which are amenable to mass production are being reared and marketed by several insectaries, both Government and Private. These are being released against several crop pests. Success with such releases requires appropriate timing, dosage and sufficient number of releases.

With the introduction of exotic pests like the scolytid coffee berry borer, *Hypothenemus hampei* (Ferrari), coconut mite, *Aceria guerreronis* and serpentine leaf-miner, *Liriomyza trifolii* and also some of the indigenous pests like *Helicoverpa armigera* and *Spodoptera litura* becoming increasingly more serious, biological control should serve as a major component of IPM.

Indigenous Parasitoids

A successful parasitoid should have a high reproductive rate, good searching ability, host specificity, be adaptable to different environmental conditions and be synchronized with its host (pest). No parasitoid has all these attributes, but those with several of the above characteristics will be more important for use in suppressing pest populations.

In nature, several parasitoids been observed to be potential bio-agents of serious crop pests. Over a dozen parasitoids have been recorded on the citrus mealybug *Nipaecoccus viridis.* However, *Anagyrus dactylopii* was dominant, parasitizing up to 90 % in the field (Ali 1957; Subba Rao et al. 1965).

On cabbage, cauliflower and other cole crops, diamondback moth (DBM), *Plutella xylostella* is a major pest. At Anand, Yadav et al. (1975) recorded up to 72 % parasitism by *Cotesia plutellae.* In Karnataka and Tamil Nadu, *C. plutellae* was known to cause up to 80 % parasitism (Jayarathnam 1977; Nagarkatti and Jayanth 1982). In the Nilgiris, *Diadegma semiclausum* provided parasitism ranging from 2.32 to 68 % (Chandramohan 1994).

The potential indigenous larval parasitoids recorded on *H. armigera* in the pigeonpea and chickpea ecosystems are the ichneumonid early larval parasitoids *Campoletis chlorideae*, *Eriborus argenteopilosus* and tachinid late larval/larval-pupal parasitoids**,** *Goniophtalmus halli, Senometopia* (*Carcelia*) *illota* and *Palexorista laxa* (Bilapate et al. 1988). Indigenous natural enemies play an important role in the integrated pest management of rice.

Indigenous Predators

In India, several predators have been identified as potential biocontrol agents. For instance, more than 60 arthropod species have been recorded as predators of *Helicoverpa armigera* (Hübner). The important predators found feeding on *H. armigera* in India are chrysopids, anthocorids, ants, coccinellids and spiders (Manjunath et al. 1989; Duffield 1993, 1995). Chrysopids form an important group of predators. A number of studies have been conducted on the biology, population ecology, feeding potential and rearing of the potential ones such as *Chrysoperla zastrowi sillemi* (Esben-Petersen), *Mallada boninensis* (Okamoto), *Mallada astur* (Banks) and *Apertochrysa sp.* (Krishnamoorthy and Nagarkatti 1981; Patel et al. 1988; Singh et al. 1994; Bakthavatsalam et al. 1994).

The important indigenous coccinellids include *Coccinella septepunctata* Linnaeus, *Scymnus coccivora* Ayyar, *Chilocorus nigrita* Fabricius, *Cheilomenes sexmaculata* (Fabricius) and *Brumoides suturalis* (Fabricius). Amongst syrphids, the important ones include *Ischiodon scutellaris* (Fabricius), *Paragus serratus* (Fabricius) and *Paragus yerburiensis* Stuckenberg.

Aphidophagous coccinellid, *C. septempunctata* is more abundant in areas with low average temperature viz., northern parts of India. It plays important role in natural suppression of aphids like *Myzus persicae* (Sulzer), *Brevicoryne brassicae* (Linnaeus) and *Lipaphis erysimi* (Kaltenbach) infesting *rabi* oilseeds and cole crops. Similarly, syrphids like *I. scutellaris* and *Paragus* spp. are also found in very high numbers feeding on these aphids. *C. sexmaculata*, on other hand, is more abundant in warmer areas of southern India and it keeps aphid like *Aphis craccivora* Koch, infesting groundnut and pulses, at lower ebb during summer and *kharif* season.

Mass production techniques for these coccinellids (Joshi et al. 2003) and syrphids (Joshi et al. 1998) have been developed at the Project Directorate of Biological Control, Bangalore and are being multiplied throughout the year. However, there is need to evaluate these natural enemies on large-scale, either in open fields or at glasshouses.

Amongst indigenous coccidophagous coccinellids, *C. nigrita* has been utilized through inundative release, not only against *Melanaspis glomerata* (Green) but also on several other diaspine scales including red scale of citrus (Singh 1994). Other important coccinellids in this group are *Pharoscymnus horni* (Weise) and *S. coccivora*. These two play important role of assisting two major coccinellids viz., *C. nigrita* and *C. montrouzieri*, respectively in different fruit crops. By virtue of their small size, they are able to enter leaf sheath and crevices of bark, where crawlers of coccids generally reside, and feed on them at early stage of crop infestation.

For leaf and plant hoppers, colonization of mirid predator *Cyrtorhinus lividipennis* for which now rearing technique is available (over 1500 predators could be reared on 1 cc *Corcyra* egg), has proved to be effective, if releases are carried out @ 100 mirid bugs or 50–75 eggs/m^2 at 10 day interval. Weeds like *Cyperus sp.* help in off-season survival of mirid bug through harbouring plant hoppers. Predation by mirid bug was more on BPH resistant rice variety PTB 33. The presence of any combination of 3 nos./hill of spider *Lycosa preudoannulata, Oxyopus javanus* and *Tetragnatha sp.* checked the population of BPH and WBPH.

The coccinellid predator, *Cryptolaemus montrouzieri* though exotic has established well. It has proved to be very effective against the grape mealy bug, *Maconellicoccus hirsutus* (Singh 1989). Release of 10 beetles per vine could effectively suppress the grape mealybugs in about 75 days of release (Mani and Thontadarya 1988a). Dichlorvos, chlorpyriphos and all the commonly used fungicides at recommended concentrations are safe to all the stages *of C. montrouzieri*, thus allowing the combined use of *Cryptolaemus* with the above pesticides in the pest management programmes (Mani and Thontadarya 1988b; Babu 1986).

Amongst the different anthocorid predators recorded in other countries, *Orius* spp. appear to be the most promising, especially against thrips; examples being *Orius sauteri, Orius majusculus, Orius laevigatus* and *Orius insidiosus*. In India, anthocorids have been recorded as potential bioagents of different species of thrips in various ecosystems. But, systematic work is lacking in our country on the seasonal occurrence of the different potential anthocorid predators in our country. Information is lacking on the extent of control of thrips exerted by the natural populations of anthocorid predators in the different agroecosystems. *Orius* spp. are the most common anthocorids which have been collected from different crop ecosystems. *Orius tantillus* and *O. maxidentex* are the most common species collected. (Ballal and Gupta 2011)

Production techniques

Production techniques are also available for some potential parasitoids like Trichogrammatids, *Leptomastix dactylopii, Copidosoma koehleri, Telenomus remus*, etc. and predators like *C. z. sillemi*, *Scymnus coccivora, Pharoscymnus horni, Curinus coeruleus, Coccinella septempunctata, Cheilomenes sexmaculata*, *Chilocorus nigrita, Brumoides surturalis*, *Cardiastethus exiguus*, etc. (Singh et al. 2001b; Ballal et al. 2012; Ballal and Gupta 2011).

Conservation Biological Control

The conservation of natural enemies is probably the most important and readily available biological control practice available to growers. Natural enemies occur in all production systems, from the backyard garden to the commercial field. They are adapted to the local environment and to the target pest, and their conservation is generally simple and cost-effective. With relatively little effort the activity of these natural enemies can be observed. For example, parasitized aphid mummies are almost always present in aphid colonies. These natural controls are important and need to be conserved and considered when making pest management decisions. In many instances the importance of natural enemies has not been adequately studied or does not become apparent until insecticide use is stopped or reduced. Often, the best we can do is to recognize that these factors are present and minimize negative impacts on them. If an insecticide is needed, every effort should be made to use a selective material in a selective manner.

Conservation biological control practices such as refuges for natural bioagents, conserving weed plants harbouring predators and egg parasitoids, use of safer pesticides, judicious and selective use of non-persistent pesticides, strip treatment, spot treatment, etc. have been found to be effective conservation techniques in several crop ecosystems (Singh 2002). Use of kairomones, synomones, pheromones, adjuvants, etc. to increase the searching ability and retention of parasitoids, build-up population of biocontrol agents by providing artificial structures, food, alternate host, suppression of ants, etc., provision of grain sorghum in cotton plot, which serves as a source for natural enemies, etc are some conservation techniques.

Habitat manipulation techniques (to improve the population and performance of natural enemies) are easily incorporated into home gardens and even small-scale commercial plantings, but are more difficult to accommodate in large-scale crop production. There may also be some conflict with respect to pest control because of the difficulty in targeting the pest species as the refuges may be used by the pest insects as well as natural enemies. Habitat manipulation involves altering the cropping system to augment or enhance the effectiveness of a natural enemy. Many adult parasitoids benefit from sources of nectar and the protection provided by refuges such as hedgerows, cover crops and weedy borders. Mixed plantings and the provision of flowering borders can increase the diversity of habitats and provide shelter and alternative food sources. They are easily incorporated into home gardens and even small-scale commercial plantings, but are more difficult to accommodate in large-scale crop production. There may also be some conflict with pest control because of the difficulty of targeting the pest species as the refuges could be used by the pest insects as well as natural enemies.

Natural enemies may be conserved by using insecticides or formulations which are least harmful and by timing applications to reduce the impact on beneficial arthropods. Natural enemy populations may be enhanced by increasing the diversity of plant species in the vicinity of the crop, changing cultural practices to ensure continuous availability of hosts and by providing alternative food sources (Pawar 1986). Ballal and Singh (2001) reported that non-intervention and thus conservation of natural enemies to be the best strategy for *Helicoverpa armigera* management in the sunflower ecosystem.

Classical Biological Control

Biological control agents that are not host specific may pose threats to at-risk species and constraints have been applied to the types of organisms that may be used. The requirement for increased host specificity means exotic polyphagous predators are less appropriate for introduction and more research emphasis has been placed on parasitoid species (Goldson et al. 1994).

In many instances, the complex of natural enemies associated with an insect pest may be inadequate. This is especially evident when an insect pest is accidentally introduced into a new geographic area without its associated natural enemies. To obtain the needed natural enemies, we turn to classical biological control.

Classical biological control has proved its potential in our country with respect to some of the introduced natural enemies. The exotic natural enemies which have proved effective through augmentation include egg parasitoid *Telenomus remus* (Origin: Papua New Guinea) against *S. litura* infesting tobacco, the egg larval parasitoids *Chelonus blackburni* (Origin: Hawaii) and *Copidosoma koehleri* (Origin: Australia) against potato tuber moth *Phthorimaea operculella*. Not all introduced parasitoids were successful in managing the target pests.

Exotic parasitoids that have successfully established in our country include the encyrtids *Encarsia perniciosi* and *Aphytis diaspidis* for control of San Jose scale, *Quadraspidiotus perniciosus* and similarly, *Leptomastix dactylopii* against citrus mealybugs.

L. dactylopii introduced from the West Indies in 1983 is a fairly specific parasitoid of *Planococcus citri*, possessing excellent host searching ability. Field release of *Leptomastix* resulted in its establishment in mixed plantations of citrus and coffee, and also in citrus orchards in several parts of Karnataka, resulting in control of *P. citri* within 3–4 months. No insecticidal sprays were required subsequently for the control of *P. citri* in the following season (Manjunath 1985; Krishnamoorthy and Singh 1987; Nagarkatti et al. 1992).

Three strains of *E. perniciosi* viz., Californian, Russian and Chinese, were introduced for the control of *Q. perniciosus*. In addition, *A. diaspidis* (origin: Japan) was introduced from California. All the strains could establish and the Russian strain of the parasitoid gave 89 % parasitism in Himachal Pradesh. *A. diaspidis* in combination with *E. perniciosi* gave 86.5 % parasitism. In Kashmir, the Russian and Chinese strains appeared to be superior. American and Chinese strains of *E. perniciosi* were also released in the Kumaon hills of Uttar Pradesh; the population of the pest was reduced by about 95 %. In Kashmir, releases of *E. perniciosi* and *Aphytis proclia* resulted in an increase of parasitism from 8.9 to 64.3 %. Studies on the biology of *E. perniciosi* revealed that the multiplication rate of the parasitoid was over 10 times. In apple, release of *E. perniciosi* or *A. proclia* @ 2000/ infested tree gave effective control of San Jose scale (Rao et al. 1971; Singh 1989).

In the tobacco, cabbage and cauliflower ecosystems, the exotic parasitoid *T. remus* Nixon has proved to be potential parasitoid for the management of *S. litura*. Tobacco IPM has been successfully field demonstrated in farmers' field in Andhra Pradesh (PDBC-ICAR, 1999–2000).

Combination of exotic parasitoids, *C. blackburni* and *C. koehleri* with *Bt* products and granulosis virus has been found effective in managing the potato tuber moth, *P. operculella* in potato fields and in storage (Singh 1994).

For the management of the coffee berry borer, *H. hampei,* the bethylid parasitoids, *Prorops* *nasuta* and *Cephalonomia stephanoderis* were imported from Mexico in 1995 and the eulophid parasitoid, *Phymastichus coffea* and another consignment of *P. nasuta* from Colombia in 1999. The first test field releases were made in January–February, 1996. Though recoveries of *P. nasuta* and *C. stephanoderis* could be made, *P. nasuta* could not establish both in the laboratory and in the field in spite of repeated field releases. *C. stephanoderis* has established in several areas of Kodagu district, Wyanad and Lower Palanis. Carry over of the parasitoid from one season to the other has also been observed. More than 10,000 females of *P. coffea* have been released and establishment in small numbers has been observed (Sreedharan et al. 2001).

The spiraling whitefly, *Aleurodicus dispersus*, a native of the Caribbean region and Central America, probably came to India from Sri Lanka or the Maldives. It was first reported in 1993 from Kerala and later from other parts of peninsular India and the Lakshadweep islands. The pest is highly polyphagous and has been recorded on 253 host plants in India. Two aphelinid parasitoids, *Encarsia guadeloupae* and *E. sp.* nr. *meritoria*, have been fortuitously introduced together with the host into India. With the accidental introduction of both species of *Encarsia* into India, there has been a perceptible reduction in the population of *A. dispersus* (Ramani et al. 2002).

One of the most recent and significant success stories in the field of classical biological control is that of the excellent control of papaya mealy bug through introduction and field releases of exotic natural enemies. The papaya mealybug *Paracoccus marginatus* W & G was first recorded on papaya plants from Coimbatore in 2008 and later spread to different states viz. Kerala, Karnataka, Maharashtra and Tripura. Chemical pesticides could not give permanent relief and repeated use of chemical pesticides resulted in toxicity hazards, pollution and harmful effects on non-target beneficials. The natural enemies existing in nature like *Spalgis epius, Cryptolaemus montrouzieri* and *Scymnus coccivora* could not keep the papaya mealy bug population under check. NBAII imported three species of parasitoids *Acerophagus papaya, Pseudoleptomastix mexicana* and *Anagyrus loecki* (from USDA-APHIS at Puerto Rico), which are known to effectively suppress the papaya mealy bug in its native range. The parasitoids could be successfully multiplied and supplied to stake-holders all over the country. Inoculative releases of the parasitoids were also made in farmers' fields in different villages. The parasitoids could successfully establish in all the areas of release and suppress the papaya mealybug infestation on different crops (Shylesha et al. 2010). NBAII also trained entomologists/plant protection officials from SAUs, ICAR Institutes, KVKs, CIPMCs, Government Biocontrol Laboratories and Central Sericulture Research and Training Institute on the mass production, field release and conservation of the parasitoids.

Production and Utilization of Parasitoids and Predators

Besides introducing suitable exotic natural enemies, efforts should be made to develop more efficient and cost-effective production and utilization of indigenous natural enemies (Rabindra et al. 2003; Jalali et al. 2003). Success with field releases of natural enemies requires appropriate timing, release of the correct number of natural enemies per unit area or depending on pest density and release of quality bioagents. In many cases, the most effective release rate has not been identified as it will vary depending on crop type and target host density. Table 1 lists some of the parasitoids and predators, which could be released for the management of some major pests on different crop ecosystems.

Biological control through augmentation has gained maximum acceptance amongst sugarcane farmers of India. Use of *T. chilonis* has been effectively utilized for the management of sugarcane borers. Sugar mills have their own co-operative parasitoid production units and have contributed in a big way in adoption of biocontrol (PDBC 2000–2001; Singh et al. 2001a). Augmentation of the tachinid parasitoid *Sturmiopsis inferens* has decreased the population of shoot borers in Tamil

Table 1 Some biological control systems utilizing parasitoids

Crop/Pest	Biotic agents	Dosage per ha	Frequency of application
Sugarcane			
Chilo spp.	*Trichogramma chilonis*	50,000	Every 10 days, 8 times starting on 30-day-old crop for shoot borer and 60 days for other borers or during egg laying period
Pyrilla perpusilla	*Epiricania melanoleuca*	2–3 egg masses or 5–7 cocoons in 40 selected spots/ha	The releases are initiated before the onset of rainy season
Rice			
Scirpophaga incertulas & *Cnaphalocrocis medinalis*	*Trichogramma japonicum* *T. chilonis*	100,000	30, 37 and 44 days after transplanting (DAT)
Cotton			
Helicoverpa armigera, *Earias* spp., *Pectinophora gossypiella*	*T. chilonis*	150,000	Weekly 6 times starting from 40th day after planting or during the egg laying period
Tobacco			
Spodoptera litura	*Telenomus remus*	120,000	Five times at weekly interval
Coconut			
Opisina arenosella	*Goniozus nephantidis*	3000 adults	Need based or for each generation
	Cardiastethus exiguus	50 adults/tree	To coincide with egg or freshly hatched larval stage of the pest
Apple			
Eriosoma lanigerum	*Aphelinus mali*	1000 adults or mummies/ infested tree	Once, as soon as infestation is noticed
Quadraspidiotus perniciosus	*Encarsia perniciosi*	2000 adults/infested tree	Once, in spring
Cydia pomonella	*Trichogramma embryophagum*	2000 adults/tree	Releasing at weekly interval
Citrus			
Planococcus citri	*Leptomastix dactylopii*	3000 adults	Need based; under expert supervision
Tomato			
Helicoverpa armigera	*Trichogramma brasiliense* *T. pretiosum/T. chilonis*	50,000	Weekly interval/six times from 25th day after transplanting or during egg laying period

Nadu and the parasitoid permanently colonized in some pockets (Singh 1994). Similarly, inundative releases of *Isotima javensis* has given good results in the control of top borer, *Scirpophaga excerptalis* in north India.

There are several potential parasitoids in nature which are important mortality factors of major pests. On citrus butterfly *Papilio demoleus* Linnaeus, egg parasitoid *Trichogramma chilonis* Ishii parasitized up to 76 % and *Telenomus sp.* nr. *incommodus* 78 % in February (Krishnamoorthy and Singh 1988; Jalali and Singh 1990). *Distatrix papilionis* is the dominant parasitoid of caterpillars and *T. chilonis*, *T. incommodus* and *D. papilionis* caused a cumulative parasitism of 88 % (Krishnamoorthy and Singh 1988). *T. chilonis, Melalophacharops sp.* and *D. papilionis* could be utilized for the biological suppression of butterflies attacking citrus. The eggs of fruit sucking moth, *Othreis fullonia* are successfully parasitized by *T. chilonis*, which suggests the possibility of utilizing *T. chilonis* for the control of this pest (Dodia et al. 1986).

Notable success has been achieved in the biosuppression of the hopper *Pyrilla perpusilla* in some states by the colonization/redistribution of the lepidopteran parasitoid, *Epiricania melanoleuca*. Misra and Pawar (1984) reported that this parasitoid when released @ 400,000–500,000 eggs or 2000–3000 cocoons/ha in eastern UP, West Bengal, Orissa, Karnataka, Kerala, Maharashtra, Rajasthan, Andhra Pradesh and Madhya Pradesh gave complete control of the pest. Pawar (1979) reported that in July–September, if 20–60 % parasitism of nymphs and adults are recorded there is no need to panic even if outbreak like situation is noticed.

Indigenous parasitoids play a major role in the management of the coconut black-headed caterpillar in the coconut ecosystem. Field release of the three stage specific *Opisina arenosella* parasitoids *viz Goniozus nephantidis, Elasmus nephantidis* and *Brachymeria nosatoi* at fixed norms and intervals in a heavily infested coconut garden (2.8 ha) for a period of 5 years resulted in highly significant reduction in *Opisina* population (Sathiamma et al. 2000). Follow-up observations revealed that even after 3 years no build-up of the pest was noted in the released site. The anthocorid predator *Cardiastethus exiguus* and *G. nephantidis* have been observed to be highly amenable to mass production and they have also proved to be highly effective against the egg and larval stages of *O. arenosella* as indicated in the recent field trials conducted at Kerala and Karnataka (Venkatesan et al. 2008).

The sugarcane woolly aphid, *Ceratovacuna lanigera,* was observed as a serious pest of sugarcane and reported in outbreak proportions from western and southern India (Rabindra et al. 2002; Joshi and Viraktamath 2004). The parasitoids which were recorded on this pest in Nagaland included *Aphelinus desantisi*, *Encarsia falvoscutellum*, *Diaeretiella rapae*, *Anagyrus sp.* and *Antocephalus sp.* (Tripathi 1995). In Assam, Jorhat *Encarsia flavoscutellum* was observed in abundant numbers parasitising woolly aphids. The heavy incidence of this parasitoid could prevent the further spread of the woolly aphid population. *Dipha* and *Micromus* are potential predators of SWA in nature, which keep the pest population under control.

In the cotton ecosystem, the indigenous parasitoid *Bracon greeni* gave satisfactory control of spotted and spiny bollworms *Earias* spp. in Karnal, Haryana (Khan and Rao 1960) and for the control of *Pectinophora gossypiella* in Coimbatore (Swamiappan and Balasubramanian 1980).

In rice ecosystem, conservation and inundative release of the egg parasitoid *T. japonicum* and *T. chilonis* along with the predator *Cyrtorhinus lividipennis* have given promising results. Weekly releases of *T. japonicum* and *T. chilonis* @ 100,000/ ha starting after a month of transplanting is recommended for the control of stem borer, *Scirpophaga incertulas* and leaf roller, *Cnaphalocrocis medinalis*. A total of three releases for *Rabi* and *Kharif* crops are sufficient. The trials conducted at Tamil Nadu, Maharashtra, Punjab, Assam and Kerala proved that Biocontrol Based Integrated Pest Management (BIPM) was either at par or better than farmers' practice in all the places (PDBC-ICAR 2001–2002).

The BIPM schedule for pest management includes releases of *C. z. sillemi* for sucking pests. This schedule was successful in Karnataka, Maharashtra and Gujarat

At the erstwhile Project Directorate of Biological Control (now NBAIR), the two indigenous early larval parasitoids of *H. armigera*—*C. chlorideae* and *E. argenteopilosus* could be continuously reared on alternate laboratory hosts and several basic studies conducted (Venkatesan et al. 1995; Ballal et al. 2000; Ballal et al. 2001b).

Geographical strains of *C. chlorideae* were obtained from different parts of the country and their biological parameters and performance evaluated and it was found that the Sehore strain was most efficient (Ballal and Ramani 1994). Variations were observed in the performance of *C. chlorideae* populations collected from different crop ecosystems. The lab-reared parasitoids which were originally from the pigeonpea ecosystem could not efficiently parasitise *H. armigera* larvae from the cotton ecosystem, whereas the parasitoids from the cotton ecosystem were capable of parasitizing more than 40 % of the larvae of cotton ecosystem (Ballal et al. 2001a). The studies clearly indicated that the performance of *C. chlorideae* is largely governed by the host plants on which the pest is found. Bajpai et al. (2002) reported that on chickpea plants, the chemical cues released during feeding by the

H. armigera was essential for *C. chlorideae* to be attracted to the infested plants and to induce parasitism. Parasitism was also governed by host plant variety (Ballal and Gupta 2003). This was also true for *Trichogramma* spp. (Ballal and Singh 2003).

In a successful attempt to bridge the gap between research and commerce through a path breaking work involving studying for 325 generations, a strain of *T. chilonis* with physiological tolerance to 0.07 % of endosulfan has been developed for the first time. The strain is distinctly superior (98 % control) to endosulfan spray (72.0 %) in the control of cotton bollworm. This strain has been transferred to M/s.Excel Industries Limited, Mumbai. It is multiplied on a large scale and distributed to the farmers under the trade name "Endogram". Endogram technology is registering a gradual spread in different states. In three years, 29700 ha of cotton and vegetables crops were treated with endogram in six different states.

This strain has been further developed for multiple tolerances to the recommended dosages of monocrotophos (0.05 %) and fenvalerate (0.002 %). Multiple insecticides tolerant strain of *T. chilonis* is for use on cotton, vegetables and rice, etc. where several insecticides. The strain is tolerant to endosulfan, monocrotophos and fenvalerate. It also shows moderate to high cross-tolerance for other insecticides too.

A strain of *T. chilonis* which can tolerate a temperature of 36 °C has been developed. High temperature tolerant strain of *T. chilonis* and *T. japonicum* can be utilized during months when temperatures are more than 35 °C. The strain can tolerate the temperatures up to 38 °C. It is useful against the sugarcane shoot borer and top borer and also others pests on cotton and vegetable crops during hot months. High host searching strain of *T. chilonis*, *T. japonicum*, *T. achaeae* and *T. bactrae* can be used on several pests as this strain has better host searching ability and higher fecundity. These strains can be used on a number of crops in milder climatic conditions (Jalali and Singh 1993; Jalali et al. 2006; Ballal et al. 2009b).

Mealy bugs like the common mealy bug (*Planococcus citri*), grape mealy bug (*Maconellicoccus hirsutus*), mango mealy bug (*Rastrococcus iceryoides*), spherical mealy bug (*Nipaecoccus viridis*), striped mealy bug (*Ferrisia virgata*), oriental mealy bug (*Planococcus lilacinus, P. pacificus, P. robustus*) and pineapple mealy bug (*Dysmicoccus brevipes*) cause serious damage and decrease the productivity and marketability of the produce. Some mealybugs have also been able to develop resistance to insecticides.

Cryptolaemus montrouzieri was introduced from Australia into India in June, 1898 for the control of soft green scale *Coccus viridis.* It could not establish on soft green scale. Later, it was reported as a common predator of many species of mealy bugs and to some extent on scale insects in Karnataka (Rao et al. 1971). In 1977, an insectory was established at Central Horticultural Experiment Station, Chethalli, Kodagu, Karnataka for its multiplication. This coccinellid can now be successfully mass produced and field released (Joshi et al. 2003). The production cost of 100 beetles in some private companies is Rs 70 (As per the 2000 price index). This beetle can also be reared using a semi-synthetic diet. A single grub is known to feed about 1500 eggs or 880 nymphs or 30 adult females of *M. hirsutus* (Mani et al. 2014). Now commercial insectaries are also producing and supplying *C. montrouzieri* to the growers. In fruit and plantation crops, the beetles are released @ 5–50 per plant, depending upon the severity of infestation and crop canopy. On each mealy bug infested plant of coorg mandarin, robusta coffee, arabica coffee and san–ramon coffee release of 10, 5, 3 and 2 beetles per plant resulted in reduction of mealy bug population and by 5th week the pest population reduced to negligible level. Beetles were released in 13 mixed planted orchards (citrus and coffee) and satisfactory results obtained. Field releases of *C. montrouzieri* @ 20 adults per tree gave excellent control of *F. virgata, M. hirsutus* and *P. lilacinus* on guava within 50 days in the presence of other local natural enemies. It was also found to be highly effective in suppressing the populations of *M. hirsutus* in grapes within 75 days. The predator was found effective in suppressing the mealy bugs on citrus, guava, grapes, mulberry, coffee, mango, pomegranate, custard apple, ber etc. and

Table 2 Biological control of mealy bugs and scale insects with *Cryptolaemus montrouzieri*

Crop	Species	Place	Result
Araucaria	*Eriococcus araucariae*	Karnataka	Completely wiped out
Brinjal	*Coccidohystrix insolita*	Karnataka	Suppressed
Crotons	*Planococcus minor*	Karnataka	Brings down the population
Ficus	*Chloropulvinaria psidii*	Karnataka	Managed successfully
Hibiscus	*Aphis gossypii*	Karnataka	Suppressed successfully
Jacoranda	*Saissetia hemisphaerica*	Karnataka	Suppressed
Jasmine	*Pseudococcus longispinus*	Karnataka	Kept under check
Mulberry	–	Karnataka	–
Mussaenda	*Orthesia insignis*	Karnataka	Suppressed
Neem	*Chloropulvinaria maxima*	Karnataka	Kept under check
Sapota	*Coccus viridis*	Karnataka	Suppressed
	Planococcus citri	–	–
Tomato	*Planococcus citri*	Karnataka	Suppressed
Ber	*Nipaecoccus viridis, P. lilacinus, P. citri M. hirsutus* and *Drepanococcus chiton*	Karnataka	Suppressed
Chow-chow	*P. lilacinus*	Karnataka	Suppressed
Citrus	*Planococcus citri* and *Nipaecoccus viridis*	Karnataka	Suppressed successfully
Coffee	*Planococcus* spp.	Karnataka	Suppressed successfully
Custard apple	*M. hirsutus, P. citri, P. lilacinus, F. virgata* and *N. viridis.*	Karnataka and Andhra Pradesh	Suppressed
Grapevine	*Maconellicoccus hirsutus* and *Planococcus citri*	Karnataka and Andhra Pradesh	Suppressed successfully
Guava	*Chloropulvinaria psidii Aphis gossypii Drepanococcus chiton Ferrisia virgata Planococcus citri* and *P. lilacinus*	Karnataka and Tamil Nadu	Suppressed successfully
Mango	*Chloropulvinaria polygonata Ferrisia virgata Planococcus citri Rastrococcus iceryoides* and *R. invadens*	Karnataka	Suppressed
Pomegranate	*Siphoninus phyllireae Maconellicoccus hirsutus, Planacoccus citri, P. lilacinus, Ferrisia virgata* and *Nipaecoccus viridis*	Karnataka	Suppressed

green shield scale on sapota, mango, guava, brinjal and crotons in Karnataka. It did not seriously impair the efficiency of local biocontrol agents (Table 2).

The conventional pesticides such as dichlorvos. chlorpyrifos, dicofol, fish oil rosin soap and most of the botanicals and fungicides are safe to *C. montrouzieri*.

C. montrouzieri does not feed on the mealybugs mummified due to parasitisation by *Anagyrus dactylopii*. *C. montrouzieri* in the presence of the encyrtid parasitoid *Anagyrus dactylopii* gave excellent control of *M. hirsutus* in vineyards. Similar control of *Ferrisia virgata* was achieved on guava with *C. montrouzieri* in the presence of the encyrtid parasitoid *Aenasius advena* (Mani et al. 1990). In Karnataka, *C. montrouzieri* although was found on *Dactylopius opuntiae* did not seriously impair the effectiveness of *Dactylopius* in controlling the weed *Opuntia.*

Chrysopids In India, 65 species of Chrysopids belonging to 21 genera have been recorded from various crop ecosystems. Some species are distributed widely and are important natural enemies for aphids and other soft bodied insects. Amongst them, *C. z. sillemi*, *Mallada boninensis*, *Apertochrysa crassinervis* and *Mallada astur* are the most common. The first two have been used in cotton ecosystem for protection from aphids and other soft bodied insects. *C. z. sillemi* has been recorded on cotton, green gram, sorghum, maize, safflower, sunflower and pigeonpea, predating on the pest like safflower aphid, maggots of safflower fruit fly, eggs of pentatomid bugs on green gram, sorghum aphid, eggs of Pyrilla, cotton aphid and leaf hoppers. In Himachal Pradesh, *C. z. sillemi* feeds on woolly aphid *Eriosoma lanigerum* colonies and hibernates in cocoons as prepupae from first week of November to early March.

C. z. sillemi can be multiplied on the eggs of *C. cephalonica.* A monocrotophos tolerant strain of *C. z. sillemi* has been selected by Gujarat Agricultural University, Anand. *C. z. sillemi* is now used extensively all over the country. *C. z. sillemi* is multiplied for commercial use by adopting a two step rearing. In the first step larval rearing, 120 three-day-old chrysopid eggs are mixed with 0.75 ml of UV-irradiated *Corcyra* eggs in a plastic container (group rearing). On hatching, the larvae start feeding and on the 3rd day the larvae are transferred to 2.5 cm cubical cells of plastic louvers as the second step individual rearing. Total quantity of *Corcyra* eggs required for rearing 100 chrysopid larvae is 4.25 ml. They can also be produced on semi synthetic diet, which includes the utilization of wastes from other insect production units.

The cost of production and application of *C. z. sillemi* @ 100,000/ ha came to Rs 744, which could be reduced when the production capacity was increased. Attempts are on to reduce the cost involved in field use of chrysopids through manipulation of the dosages. Normally, chrysopids are recommended for use against different crop pests @ 50,000 or 100,000 1st instar larvae/hectare, 4–6 larvae/plant or 10–20 larvae/fruit plant are released. Depending on the situation, two releases are recommended. They are released on the plants along with sawdust, or dropped from the corrugated paper strips.

Anthocorids In India, very few attempts have been made to rear the anthocorid predators. Mukherjee et al. (1971) tried a synthetic diet for the rearing of *X. flavipes* (Reut.). Mass rearing methods have been standardised for four potential anthocorid predators, *Cardiastethus exiguus* Poppius (Ballal et al. 2003a), *Blaptostethus pallescens* Poppius (Ballal et al. 2003b) and *Xylocoris flavipes* (Reuter) (Ballal et al. 2013) and *Orius tantillus* Motshulsky (Gupta and Ballal 2006).

Techniques were not available to mass rear *Orius* spp. in India till recently. At the NBAIR, Bangalore, methods have now been standardised to multiply *Orius tantillus* on different host eggs. Earlier studies had indicated that the progeny production by *Orius maxidentex* when reared on sorghum midge, was 35.10 per female and 23.61 per female when reared on thrips. There are problems associated with continuous multiplication of host insects like thrips and midges. Hence other alternate laboratory hosts eggs were tried. *O. tantillus* could be continuously multiplied for 12 generations on UV irradiated *C. cephalonica* eggs, however, the progeny production was very low, the mean value being 3.1 per female. It is clear that there is a need to improve the diet provided to improve the progeny production. The UV-irradiated eggs of *Sitotroga cerealella* was also tried. *O. tantillus* could be reared more efficiently on *S. cerealella* eggs than on *C. cephalonica* eggs. The optimum temperature regime for multiplication of *O. tantillus* was found to be 24 and 28 °C as progeny production was maximum at these two temperatures, the values being 28.8 and 26.2 per female, respectively.

Laboratory studies were conducted to check the feeding preference of *O. tantillus* on parasitized and un-parasitized eggs of *Helicoverpa armigera*. Results of choice and no-choice tests showed that there was significantly higher preference for un-parasitized eggs in comparison to parasitized eggs, thus indicating that it may be possible to integrate releases of anthocorids and trichogrammatids for biological control of lepidopteran pests/thrips in different crop ecosystems (Gupta and Ballal 2007).

The anthocorid species which have been commonly used for field releases are: *Anthocoris nemoralis* (Fabricius), and *Orius* spp. Anthocorids are now being commercially produced in several countries. *C. exiguus* has been field evaluated against *O. arenosella* and *B. pallescens* against onion thrips and two spotted spider mites on bhendi. Both the anthocorids have proved to be potential predators for field use (Lyla et al. 2006; Ballal et al. 2009a).

Climate Change and Biological Control Though clear evidence is lacking, it is strongly felt that climate change may alter the effectiveness of biological control. Successful biocontrol agents are highly specific to the invasive species they are targeted to control and changes in the climatic factors may alter these inter specific interactions. Tritrophic interactions between plants, herbivorous insects and their natural enemies (predators, parasitoids and pathogens) result from a long co-evolutionary process specific to a particular environment and relatively stable climatic conditions. These tri-trophic interactions would be affected by climatic conditions in diverse ways. Extreme temperatures can affect both pests and their natural enemies. A warmer climate would increase the metabolic rate of insects and their natural enemies. Studies show that metabolic rate and hence burning of resources increases monotopically with temperature, while activity is maximum at intermediate temperatures. Therefore, increased temperature could lead to reduction in longevity and realized fecundity of temperate insect parasitoids, in turn causing decrease in their efficacy. Besides, exposure to stressful temperatures could induce lethal and sub lethal damages to parasitoids, generally decreasing mobility, ability to orient themselves to attractive odours and learning capacities and increasing production of male progeny. The endosymbiont bacteria associated with the parasitoid and host could be suppressed by short exposure to high temperature.

While the effects of global atmospheric changes on vegetation and resulting insect populations ('bottom-up interactions') are being increasingly studied, how these gases modify interactions amongst insects and their natural enemies ('top-down interactions') is less clear. As natural enemy efficacy is governed largely by behavioural mechanisms, altered prey finding and prey defence may change insect population dynamics.

Long term studies on effect of climate change on pests or natural enemies have not been conducted in India. Likely, impacts of any change in climate on populations of pests are manifold. They range from expansion in the geographical range of pests, increased risk of invasion, changes in overwintering patterns, natural enemy-pest interactions, changes in population growth rates, change in crop-pest synchrony, pest control factors and finally changes in pest complexes on spatial and temporal bases. Results obtained through current modelling approaches do not account for all the factors operating. Moreover, it may not be possible to replicate the methodology of other countries in the Indian context, given the wide-ranging socioeconomic conditions and different agro-ecology, and a different approach is needed to tackle the problem. Consolidation of all existing studies done in various parts of the country may act as a foundation, which can be supplemented by incorporation of the vast resources of data from various government agencies (Sehgal et al. 2006)

In India, a number of short term studies have been conducted to investigate the effect of abiotic factors, especially temperature on pests or natural enemies. Laboratory studies have shown that a temperature of 35 °C was detrimental to the different biological stages and adult longevity of *Campoletis chlorideae*, which is a potential indigenous parasitoid of *H. armigera* (Teggeli et al. 2004). Earlier, studies have clearly indicated the adverse effect of temperature on parasitoids. Singh and Ali (2006) reported that minimum and maximum temperatures showed a negative correlation with parasitization of *H. armigera* by *C. chlorideae*. Field studies in *H. armigera* infested chickpea fields in Himachal Pradesh indicated that the activity of *C. chlorideae* ceased when the mean maximum temperature reached above 40 °C Gupta and Desh Raj (2003). In chickpea fields in eastern Uttar Pradesh, parasitic activity of *C. chlorideae* was highest (80.5 %) when maximum and minimum temperatures and relative humidity were 24.5 °C, 8.6 °C and 85 %, and was lowest (22.2 %) when the above parameters were 36.6 °C, 18.5 °C and 85 %, respectively (Pandey et al. 2005).

The abundance of whitefly (*Bemisia tabaci*) and its parasitoid (*Encarsia lutea*) was monitored under agroclimatic conditions of Haryana. The pest population had a positive correlation with temperature, while the population of parasitized pupae showed negative correlation with temperature (Sharma et al. 2004). The infestation of the Oak tasar silkworm, *Antheraea proylei* by two species of tachinid parasitoids viz., *Blepharipa zebina* Walker and *Exorista sorbillans* (causing considerable loss to the oak tasar industry in Manipur) starts from March and reaches a peak during May with rise in temperature. This study indicated that a fair prediction for uzi fly infestation can be made from the prevailing abiotic conditions (Venkatachalapathy et al. 2002).

Khan and Misra (2003) reported that the populations of both the spiders and hoppers in the upland rice ecosystem in eastern UP during kharif were negatively correlated with temperature. Predaceous coccinellids could have varying responses to high temperature. To avoid high temperature, they could enter into diapause during pupal or larval stages, or could hide in land crevices or migrate (Indu and Chatterjee 2006). The activity of predatory fauna (coccinellids, chrysopids and syrphids) on aphids (*A. gossypii*) infesting isabgol (*Plantago ovata*) were studied in a field experiment conducted in Gujarat. The predatory activity of *Coccinella septempunctata*, *C. transversalis* and *Cheilomenes sexmaculata* increased due to increase in temperature (Patel and Borad 2005). *Coccinella septempunctata* and *Ischiodon scutellaris* are the established predators of mustard aphid *Lipaphis erysimi*. Maximum temperature had a significant negative relationship with the aphid population, but was positive for *C. septempunctata* and *I. scutellaris* (Tripathi et al. 2005). The natural parasitism of the predator *C. septumpunctata* by *Tetrastichus coccinellae* (*Oomyzus scaposus*) and the number of parasitoids emerging per coccinellid increased with an increase in temperature, thus adversely affecting the performance of the predator (Singh and Singh 2003).

Commercial Production of Parasitoids and Predators

Standard techniques are now available for the successful production of several parasitoids and predators, which could be followed by commercial insectaries. India's first private insectary, Biocontrol Research Laboratory was established at Bangalore in 1981. Since then numerous companies have come up country-wide, which produce parasitoids, predators, entomopathogens, plant disease antagonists, weed killers, etc. The PDBC has compiled an infobase on bioagent producers in India (private and government). As per this infobase (Biswas et al. 2000) and Singh (2002), there are 128 organizations producing bioagents.

Biological control workers have to face several major direct technical constraints in the process of production. These problems get further compounded by artificial selection forces and the conflicting requirements for natural enemies in a mass production programme. These technical obstacles include: non-availability of long term storage techniques for the most important alternate laboratory host insect *Corcyra cephalonica* and also for Tricho cards and mechanized application technology of parasitoids and predators, not available, problems associated with male-biased sex-ratio in the laboratory cultures and maintenance of cultures during summer and winter due to unfavourable temperature and humidity conditions, cannibalizm in chrysopids and in some coccinellid larvae which necessitates individual rearing, in vivo rearing of predators as it necessitates continuous production of host insects and host plants, infestation by *Bracon* and mites in *Corcyra* culture, disease insect cultures, effective in vitro mass production techniques for natural enemies on artificial diets, need for rearing at relatively high prey densities in the case of predatory mites, leading to high costs, occurrence of microbial contaminants fungi, bacteria, viruses, protozoa and nematodes in insect cultures leading to high mortality, prolonged development, diminutive adults, wide fluctuations in the quality of insects and direct pathological effects, lack of techniques that prevent selection pressures leading to genetic deterioration of the mass-produced natural enemies and loss of effectiveness, lack of techniques that prevent behavioural changes and/or the loss of vigour through poor nutrition when reared on alternative hosts or artificial diets, non-availability of commercial artificial diet for rearing of entomophagous insects, lack of automation to produce low-cost products and lack of good standard measures for evaluating the performance of mass reared biological control agents.

Future Thrusts

- Population dynamics of the pest and the natural biological control agents to be studied in detail before introducing an exotic natural enemy
- Standard production procedures to be developed and followed by all insectaries
- Strict quality control protocols to be followed by all insectaries
- Uniform release and evaluation techniques to be followed by all biological control researchers, which would enable the comparison of results
- In-depth studies on tri-trophic interactions between the pest, parasitoid and host plant
- Large-scale field trials to evaluate potential parasitoids in different agro-climatic regions
- Studies on kairomonal interventions to improve the performance of parasitoids
- Development of superior strains of parasitoids (insecticide tolerant, high temperature tolerant, with high searching ability, etc.)
- Climatic pattern mapping and climate mapping of a region are important in terms of risk assessment of pest as well as for biocontrol introductions. Eco-climatic assessment can provide valuable insight into species distribution, in relation to relevant climate data, particularly relating to assessment of the potential establishment of a particular biocontrol species.
- Future biocontrol attempts must consider climate variables in evaluating long term effectiveness
- Future research should concentrate on: (a) The physiological adaptations or ecological implications of exposure of parasitoids/predators/microbials to extreme climatic conditions and on the relationship between physiological adaptation and integration of a species within an ecosystem. (b) The over wintering strategies in parasitoids in relation to climate change. (c) Effect of climate change on tri-trophic interactions.
- The outcome of our research should enable us to answer some pertinent questions: (a) Could we adjust the practice of biological control by changing release schedules to compensate for the effects of climate? (b) Will the effect of climate be stronger on parasitoids and predators than on the prey insects? (c) How changes in herbivore and plant quality (including semiochemical emissions) following a rapid climate change affect a parasitoid or predator's life history traits.

Suppression of insect pests is of paramount importance considering that they can cause about 15–20 % loss in agricultural production. The present paper highlights the potential as well as proven technologies of biological control that can be commercialized and upscaled to reach farmers. The future of "insecticide-less" pest management will be driven by a bouquet of parasitoids and predators complimented by entomopathogens.

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