TENTH DR. S. PRADHAN MEMORIAL LECTURE
August 27, 2018

Challenges to the Biological Control Practices in India

By
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Dr. S. Pradhan
May 13, 1913 - February 6, 1973
Dr. S. Pradhan - A Profile

Dr. S. Pradhan, a doyen among entomologists, during his 33 years of professional career made such an impact on entomological research and teaching that Entomology and Plant Protection Science in India came to the forefront of agricultural research. His success story would continue to enthuse Plant Protection Scientists of the country for generations to come.

The Beginning

Shyam Sunder Lal Pradhan had a humble beginning. He was born on May 13, 1913, at village Dihwa in Bahraich district of Uttar Pradesh. He came from a middle class family. His father, Shri Gur Prasad Pradhan, was a village level officer of the state Government having five sons and three daughters.

After initial studies at a nearby village school, Pradhan completed his primary education from Lucknow and passed High School Examination of U.P. Board from Govt. High School, Bahraich, in 1928, with distinction in Mathematics. He then moved over to Radhaswamy Educational Institute at Agra from where he passed Intermediate Examination of U.P. Board in 1930, in first Division and was awarded a Gold Medal. Thereafter, he joined Lucknow University, where he topped the University in B.Sc. degree examination in 1932 and obtained his M.Sc. degree in 1934. He joined as Research Scholar in the same University under the able guidance of the eminent Zoologist, Prof. K.N. Bahl. He worked on functional morphology of insects for which he was awarded D.Sc. degree in 1938 and his thesis was adjudged the best among those submitted to Lucknow University during the year. Later, in 1948, he was also awarded Ph.D. degree from the same university for his research in insect toxicology carried out at Rothamsted Experimental Station, United Kingdom.

The Career

After completing his D.Sc. degree, Dr. Pradhan initially worked on sugarcane pests for a brief period under a scheme of Indian (then Imperial) Council of Agricultural Research at Gorakhpur, U.P. Thereafter, he joined Indian (then Imperial) Agricultural Research Institute in 1940 as Assistant Entomologist at the Institute’s sub-station at Karnal (Haryana), where he did his famous work on insect ecology. In 1946, Government of India sent Dr. Pradhan to Rothamsted Experimental Station, U.K. for training in insect toxicology. After his return from U.K., he established the country’s first school of insect toxicology, in 1948, at the Division of Entomology, IARI, New Delhi. With the creation of Post-Graduate School at the Institute, Dr. Pradhan became the first Professor of Entomology in 1958. He became Head of the Division in 1962 and continued till February 5, 1973 when he left the mortal world, a few months before his scheduled retirement from service.

Contributions to Science and Society

Dr. Pradhan was a visionary and scientist par excellence. Having versatile interests, he contributed significantly to various aspects of entomological research, teaching, scientific documentation and popularisation of Entomology and Plant Protection. His numerous contributions in fundamental and applied aspects are not feasible to be enlisted in single article. However, an attempt has been made to bring forth some of his most significant contributions in various spheres of entomological research.
The Researcher and Innovator

Dr. Pradhan’s research interest ranged from fundamental to applied aspects of Entomology. He was the first to identify and describe “gnathal glands” in coleopterans. His earlier work on morphology of insects led to the understanding of the homology of male genitalia, regeneration of mid-gut epithelium and function of Malpighian tubules in coccinellid beetles. His work on coiling and uncoiling mechanism of proboscis in Lepidoptera was yet another important finding to fill a lacuna in the then existing knowledge. These studies still find a place in standard books of Entomology.

Having deep understanding of insect-crop-environment interactions, keen observation and proficiency in mathematical derivations, Dr. Pradhan was an insect ecologist whose class was not only evident in this field but his work in various other fields of applied Entomology also bore the stamp of an accomplished ecologist. His contributions on effect of abiotic and biotic factors on insect life, population dynamics of pests, assessment and sampling of pest damage and crop losses are highly significant.

His classical work on effect of temperature on the dynamics of development of any cold blooded organism brought him immediate world recognition. He gave 2 equations depicting relationship between temperature and development at constant and variable temperatures, which were later called as Pradhan’s equations,

1. For constant temperature: \( Y = Y_0 e^{-ax^2} \)
   
   where,
   
   \( Y_0 = \) highest developmental index,

   \( Y = \) Developmental index at required temperature \( t \),

   \( x = T-t \) (\( T \) being temperature at \( Y_0 \)), and \( e \) is a constant (2.718282).

2. For variable temperature: \( Y (t_1-t_2) = \frac{Y_0 \int_{x_1}^{x_2} e^{-ax^2} dx}{t_1-t_2} \)
   
   where,
   
   \( Y (t_1-t_2) = \) Average value of developmental index corresponding to temperature fluctuation between \( t_1 \) (max.) and \( t_2 \) (min.) at which the values of \( x \) are \( x_1 \) and \( x_2 \), respectively.

The validity of these equations have been verified in several laboratories world over. Among the various temperature - development relationship equations evolved by different workers, ‘Pradhan equations’ have been found best and provided most accurate relationship. These equations evoked so much interest globally among leading development biologists that several full papers were published on his innovation. The deduction of the equations provide a glimpse of Dr. Pradhan’s mathematical acumen and insight of biophysical aspects of growth and development, a rare combination of abilities in a biologist.

Based on these equations Dr. Pradhan developed ‘Biometer’, a ready reckoner for reading the insect development at any temperature and for estimating the amount of development or the number pf
generations in any given period and under any range of temperature fluctuations by counting the number of certain cells. He tested the hypothesis by preparing biometers of several important crop pests.

Dr. Pradhan was a pioneer in insect toxicology research. One of his most important contributions was on temperature-toxicity relationship, where he showed that the susceptibility of insect to insecticides depended on the combined effect of temperature prevailing before, during and after the treatment. He was the first to demonstrate that insect response to DDT varies with post-treatment temperature. Dr. Pradhan and his illustrious student, late Dr. Ranga Rao proposed a physical theory on the mode of action of DDT based on electrophysiological evidences in 1966.

His contributions to fundamental aspects of insect toxicology included relationship between particle size of suspensions and insect mortality; the role of cement and wax layers of insect cuticle in penetration of insecticides and suitability of various diluents in insecticide formulations. He was the first to report insecticide resistance from the country and developed a strong section for work on this aspect. He demonstrated that the resistance to insecticides had two components in external (resistance to the entry of poison into insect system) and internal (resistance to the poison that has gained entry into insect system) and that these 2 components of resistance differ markedly in different species. A regular bioassay of relative toxicity of insecticides to different pest species was initiated under his leadership in order to (a) screen out most effective insecticides against different pests and (b) to detect development of resistance to different insecticides in various pests.

Dr. Pradhan evolved effective chemical control measures against various crop pests through bioassay and field trials. His ecological leanings were evident even in this field where the chemical control recommendations were directed against weaker spots in pest life cycle, timed suitably and adapted in a manner which was safe to non-target organisms and natural enemies. His critical analyses of various key pest problems of different crops for effective pest control strategies can be gauged by the biotic circuit and chronological strategy of pest control based on ecological timing and integration’ of different control strategies against sugarcane pests.

Under his leadership, work on insecticide residues was started in the Division using bioassay technique. Dr. Pradhan was one of the earliest proponents of the concept of integrated pest management (IPM). His address at the International Seminar on Integrated Pest Control, organised by him in 1969, provides a lucid account of the philosophy and feasibility of IPM strategies for different crops. His concept of double screening of natural enemies due to direct toxic effects of insecticides and indirect stress from reduced host density was a revealing analogy of IPM.

His approach to solve problems associated with grain storage on the basis of ecological requirements of grain and different stored grain pests is an essential reading material for everyone interested in storage pest management. Based on this analysis Dr. Pradhan and coworkers developed a cheap, scientifically fabricated and effective grain storage structure named as Pusa Bin and later its larger version, Pusa Cubicle.

Dr. Pradhan was the pioneer in ‘neem research’. He demonstrated the strong insect antifeedant activity of neem kernel suspension during early sixties, when botanicals were given a low priority. It has revitalised
the entire research work on neem leading to purification of bitter principles. He also demonstrated its success in field trials and advocated its use by farmers in protecting their crops during locust invasions.

He propounded the famous Biotic theory on the periodicity of locust cycles which explains the distribution and abundance of locusts both in time and space, and showed the way for the locust cycles to be nipped in the bud. He presented a paper ‘Biological control of Acridid Pests’ at the International Conference on Current and future problems in Acridology at London in 1970.

Under his leadership, studies on host plant resistance were intensified during sixties and a number of good sources of resistance to key pests of sorghum and maize were identified and later used for breeding pest resistant varieties. Also the pioneering work on evaluating world germplasm of wheat for their reaction to major storage pests was undertaken by Dr. Pradhan with co-workers which showed that host grain resistance could be used for alleviating post harvest losses in this important cereal.

The Educator
Dr. Pradhan was a gifted teacher and those whom he taught, many of them becoming eminent entomologists themselves, remember the lucidity and clarity of his lectures. Dr. Pradhan guided the research work of 65 students (45 for diploma of Associate, IARI; 1 for M.Sc. and 19 for Ph.D. degrees) in the discipline of Entomology. His popularity as a teacher could be illustrated from the fact that besides his specialised lectures in fields of ecology, toxicology and pest management, the basic course of Introductory Entomology wherein he taught dominance of insects attracted students of Entomology and other disciplines. Being the first Professor of Entomology, Dr. Pradhan drew up the curricula for M.Sc. and Ph.D. courses of the Institute.

The Visionary and Crusader
Dr. Pradhan was first to visualise the country’s need for integrated pest management instead of the conventional method of chemical control alone, which though successful at the time had started showing adverse effects. Also he emphasized that the crop protection research should have its rightful place among overall agricultural research efforts of the country.

In his later years, he published several papers and delivered talks at different fora to bring forward the causes of accentuation of pests and need for intensification in crop protection research. His last published paper *In tropics protection research more needed than production research* is a treatise on crop protection component of overall crop production scenario.

His forceful arguments for adopting Integrated Pest Management in order to fully realise the production potential of new high yielding strains of different crops, had their impact and the country adopted IPM as a national strategy, though after his demise.

The Writer
Dr. Pradhan’s scientific papers as well as popular articles all bore his characteristic clarity of thought and acumen of presenting complex subjects in simple form. Dr. Pradhan published about 200 research papers in various Indian and foreign journals, besides several popular articles in Hindi and English. He was almost a regular contributor in annual meetings of Indian Science Congress. His book on *Insect Pests of Crops*, published
by National Book Trust in 1969, and Agricultural Entomology and Pest Control, which was published by Indian Council of Agricultural Research in 1983, would always remain valuable to agricultural scientists. His chapter on Entomology: New Dimensions of Pest Control in Plant Protection Section of the Agricultural Year book of ICAR entitled New vistas in crop yield provides an exhaustive view of needs and feasibilities of managing agricultural pest problems of the country. He also wrote a chapter on Ecology of arid zone insects excluding locusts and grasshoppers in Human and Animal Ecology published by UNESCO.

The Vanguard

Besides heading the Division of Entomology of the premier national Institute for more than a decade, Dr. Pradhan was also President of Entomological Society of India for four terms. The two positions and his towering personality made him the natural leader of the country’s crop protection specialists. Dr. Pradhan was a founder member of Entomological Society of India. The Society took great strides under his stewardship. The membership of the Society increased and the Indian Journal of Entomology grew in circulation and stature. The Society celebrated its Silver Jubilee in 1964 and a National Seminar was organised under his patronage. Again in 1969, he organised the International Seminar on Integrated Pest Control as President of the Society. Dr. Pradhan was Chairman of Entomology Committee of ICAR for a number of years and guided the planning and implementation of national policies on entomological research, teaching and extension.

Recognitions

Dr. Pradhan was regarded as an authority on insect ecology, toxicology and integrated pest control, not only in India but internationally. In one such recognition, he was invited by UNESCO as one of the selected six authorities to write different chapters in the book on Human and Animal Ecology. He felt that since the invitation was because of his work at IARI, the honorarium received for writing the review article was used by him to create an endowment for award of a gold medal every year to the most outstanding post-graduate student of Entomology at IARI in the name of his father Shri Gur Prasad Pradhan. Dr. Pradhan was invited to present his Biotic theory of locust cycles to a select gathering of acridologists and locust control workers at Porton, U.K. in 1970, He was a member of FAO panel of experts on integrated pest management. Dr. Pradhan chaired three important sessions in the 14th International Congress of Entomology, held at Canberra, Australia, in August 1972. Soon after he was invited to Hawaii to advise on the preparation of syllabus for a special course on integrated pest control. Dr. Pradhan was posthumously awarded Dr. P.B. Sarkar Endowment Prize for the triennium 1971-74 for outstanding research contribution that lead to enhanced food production in India.

Indian scientists would always remain inspired by Dr. Pradhan’s work, who was rightly called ‘Father of Modern Applied Entomology’ by Late Prof. K.N. Mehrotra, Ex-Head, Division of Entomology, ICAR-IARI.
Challenges to the Biological Control Practices in India

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PRELUDE

I consider it a great honour to be identified to present the tenth Dr S. Pradhan Memorial Lecture at the prestigious Division of Entomology, ICAR-IARI, New Delhi and hereby convey my heartfelt gratitude for the same. I dedicate this lecture to late Dr S. Pradhan, the great entomologist and visionary, late Dr S. P. Singh, founder Director of the Project Directorate of Biological Control (now upgraded to ICAR-National Bureau of Agricultural Insect Resources) and a great visionary and to all my colleagues at ICAR-NBAIR, Bangalore, who as a well-knit team work towards biodiversity conservation, biological control and non-chemical modes of pest management. I consider this not only as a great privilege for me, but also as a recognition for ICAR-NBAIR.

Around the world, entomologists and pathologists are striving to control crop pests to maintain the quality and abundance of food, feed, and fiber produced by growers and different approaches are used to prevent, mitigate or control insect pests and diseases. We often find that farmers rely heavily on chemical pesticides, which may seem to be leading to spectacular improvements in crop productivity and quality, however, the common man and many of the farmers now realize that there is a threat not only to the environment, but also to human health through excessive use / misuse of agrochemicals. Hence, the topic “Challenges to the biological control practices in India” is chosen by me for the tenth Dr S. Pradhan Memorial Lecture.

ABSTRACT: The diversity of natural enemies is known to strengthen biological control. Thus one of the major focuses in practical biocontrol programmes should be to conserve the indigenous natural enemies. Intensive agricultural practices are being followed to cater to the needs of rapidly increasing human population. However, studies have clearly indicated that food can be produced in a sustainable manner by conserving biodiversity and that intensive agricultural practices (e.g. increased chemical insecticide and fertilizer applications, tillage and irrigation and heavy mechanisation) all lead to decline in the biodiversity of natural enemies. Though majority of the studies point out that natural enemy richness enhances prey suppression, some of the studies do indicate that natural enemy diversity can even lead to weakened prey suppression due to factors like intraguild predation, behavioral interference and negative selection effects. Research conducted at ICAR-NBAIR has pointed out the benefits of conserving the diversity of natural enemies and also the effects of combinations of natural enemies on pest suppression. A classic example of conservation biological control is that of the suppression of the sugarcane woolly aphid Ceratovacuna lanigera Zehntner through conservation of the indigenous predators Dipha aphidovora (Meyrick) and Micromus igorotus Banks and the parasitoid Encarsia flavoscutellum Zehntner. This was enabled through a recommendation to refrain from applying chemical insecticides. Our studies have also indicated that combinations of biocontrol agents can enhance the overall suppression of multiple crop pests as in the case of Trichogramma chilonis Ishii with Cryptolaemus montrouzieri Mulsant for
the management of brinjal shoot and fruit borer and brinjal mealybug. The compatibility of anthocorid and geocorid predators with *T. chilonis* has also been proved experimentally. Few studies point out the negative impacts of species richness; for eg. the biocontrol of cereal aphids by spiders was disrupted by high densities of large ground beetles. Thus, to ensure conservation and utilization of an array of effective natural enemies, we advocate advanced research on understanding and documenting biodiversity of pests and natural enemies, measuring the role played by specific or combinations of natural enemies on specific target pests and participatory research based on interactions between farmers, researchers and crop advisors.

**Key words**: augmentation, biodiversity, biological control, conservation, classical biological control, natural enemies

**INTRODUCTION**

The services provided by biodiversity to agriculture through pollination and pest control are valued at approx. $ 57 billion per year (Losey and Vaughan, 2006). Ecosystem functioning increasingly depends on diversity, especially in the case of natural enemy diversity for pest control. In the 1980s, ecologists viewed the shrinking biodiversity as an alarming situation (Ehlrich and Ehlrich, 1981). Field studies indicated that when number of species and functional diversity of natural enemies increase, there is a significant increase in pest suppression (Evans, 2016). There are two key gaps in understanding and utilizing the positive aspects of insect diversity: a general neglect of insects in biodiversity research and an overemphasis on their negative impacts in all other biological research areas. An insect pest or a plant disease or a weed exists in nature along with a pool of natural enemies. The major focus in applied biological control should be to select an appropriate species or combination of species from this pool and to work on a strategy to bring about the desired level of pest or disease suppression with minimal impact on non-target species. Biological control attempts have been either through conservation or augmentation of the potential indigenous biological control agents. Of more than one-and-half million insect species which occur in this world, only about 1.0% have attained the status of pests. Many species which have pestilent potential remain at low levels because of the perpetual regulatory action exerted on them by their natural enemies. Hence, for management of some of our major pests, diseases and weeds it is important to restore the natural balance through purposeful human intervention. For tackling outbreaks of indigenous pests, the management approach could be through augmentation or conservation of indigenous natural enemies. However, when we are targeting invasive species, we may have to resort to importation of exotic agents and the classical biological control approach.

Biological control which focuses on either conserving or utilizing the diversity of natural enemies has proven to be one of the most effective, environmentally sound, and cost-effective pest management approaches as it is expected to drastically cut down the use of broad-spectrum pesticides and is considered to be a cornerstone of organic farming. The fundamental problem in applied biological control is to select an appropriate species or combination of species from the pool that will bring about the desired level of pest suppression with minimal impact on nontarget species.

The advancement in agricultural technology has brought about remarkable changes in the agricultural sector. These changes have been accompanied by excessive use of pesticides. World-wide, there are 500
species of resistant insects, mites and ticks compared with only 25 in 1955 coupled with this has been the well-publicised 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 world-wide over a million people are poisoned with pesticides each year and up to 2 per cent of cases may prove fatal. At this juncture, bio-pesticides 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.

CONSERVATION BIOLOGICAL CONTROL

Conservation of natural enemies is probably the most important, readily available, generally simple and cost-effective. 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. 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. 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. Studies have indicated that chemical inputs strongly affect beneficial insects and hence compared to conventional farms, organic farms had a higher species richness and abundance of predators and parasitoids (Bengtsson et al., 2005). Effect of insecticide inputs can go beyond farm level. In Midwestern USA, it was reported that crop pest abundance increased with the proportion of harvested cropland treated with insecticides (Meehan et al., 2011).

Besides biodiversity conservation, promoting biodiversity through local and landscape practices is extremely important. Thus focus should be on ecological management of farms through measures like increasing on farm plant diversity, perennial plant cover, etc. Conservation biological control practices such as refuges for natural bio-agents, 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). Local scale intensification (eg. fewer crop species and varieties, increases in chemical pesticide and fertilizers application tillage, irrigation and mechanisation) can lead to disturbance of biodiversity. Conservation tillage or no till practices can lead to increase in the populations of predators and parasitoids. However, some carabids and coccinellids prove to be exceptions. Diversity can be increased by planting non-crop vegetation like hedgerows which enhance natural enemy abundance (Nicholls and Altieri, 2013). 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
Habitat manipulation techniques can be 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. For leaf and plant hoppers, colonization of mirid predator *Cytorhinus lividipennis* has proved to be effective. 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 pseudoannulata*, *Oxyopus javanus* and *Tetragnatha* sp. checked the population of BPH and WBPH. 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 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). Landscape heterogeneity and complexity generally benefit natural enemies. Marino and Landis (1996) observed parasitism rates to be positively correlated with landscape complexity and Gardiner *et al.* (2009) reported higher predation rates of soybean aphids by coccinellids in soybean fields where landscape heterogeneity was maintained. Tylianakis *et al.* (2007) reported higher parasitism rates across pasture, rice and coffee systems where parasitoid diversity was higher. However, according to Schmitz (2007) in 40.3% cases, predator diversity negatively influences predation, which could be due to interspecific inference or competition.

Sillou and Barnaud (2017) reported that though scientific findings suggest that natural enemy habitats are conserved through maintaining complex landscapes, the farmers’ perceptsives are totally different. Through interviews conducted with apple growers in southern France the authors concluded that generally farmers considered natural enemies as resources for biological control of pests, especially where there was guidance from public institutions in natural enemy conservation, acclimation and management strategies. However there was no such process for convincing the farmers on the importance of landscape as a resource for conservation biological control. Thus there is a clear need for a dialogue and networking.
between landscape ecologists and farmers. Growers can be encouraged to conserve biodiversity through ecological engineering, diversified crop rotations, coupling of crop and live-stock production, etc.

**Indigenous parasitoids and predators to be conserved**

**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 (Plate 1). The emphasis should be on documenting the important natural enemies which play a major role in pest suppression and conserve them. Here we are citing a few examples. *Anagyrus dactylopii* was recorded as a dominant parasitoid parasitising up to 90 per cent of citrus mealybug, *Nipaecoccus viridis* (Ali, 1957; Subba Rao et al., 1965). On cabbage, cauliflower and other cole crops, diamondback moth (DBM), *Plutella xylostella* is a major pest and *Cotesia plutellae* is an important parasitoid in Gujarat, Karnataka and Tamilnadu (Yadav et al., 1975; Jayarathnam, 1977; Nagarkatti and Jayanth, 1982), while *Diadegma semiclausum* in the Nilgiris (Chandramohan, 1994). *Campoletis chlorideae* and *Eriborus argenteopilosus* are important early larval parasitoids of *Helicoverpa armigera* in the pigeonpea and chickpea ecosystems (Bilapate et al., 1988).

On citrus butterfly *Papilio demoleus* Linnaeus, egg parasitoid *Trichogramma chilonis* Ishii parasitised up to 76 per cent and *Telenomus* sp. *nr. incommodus* 78 per cent 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 per cent (Krishnamoorthy and Singh, 1988). *T. chilonis*, *Melalophacharops* sp. and *D. papilionis* could be utilised for the biological suppression of butterflies attacking citrus. The eggs of fruit sucking moth, *Othreis fullonia* are successfully parasitised by *T. chilonis*, which suggests the possibility of utilising *T. chilonis* for the control of this pest (Dodia et al., 1986). The two indigenous early larval parasitoids of *H. armigera* – *Campoletis chlorideae* and *Eriborus argenteopilosus* are important mortality factors, especially in the pulses ecosystem. Strainal variations were observed in *C. chlorideae* based on the geographical location and the Sehore strain was observed to be 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 parasitising 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).

**Indigenous predators**

In India, several predators have been identified as potential bio-control agents (Plate 1). 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, 1994, Duffield and Reddy, 1997).

**Coccinellids**

The important indigenous coccinellids include *Coccinella septempunctata* 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. *Cheilomenes sexmaculata*, is more abundant in warmer areas of southern India and keeps *Aphis craccivora* Koch, infesting groundnut and pulses under check during summer and kharif season.

Amongst indigenous coccidophagous coccinellids, *C. nigrita* has been utilised 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.

**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, *Chrysoperla carnea*, *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. carnea* 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. carnea* feeds on woolly aphid *Eriosoma lanigerum* colonies and hibernates in cocoons as prepupae from first week of November to early March.

**Anthocorids**

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 bio-agents of different species of thrips in various ecosystems. *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.
AUGMENTATIVE BIOCONTROL

Biological control which 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). In India, innumerable attempts have been made to augment the populations of promising indigenous natural enemies (Plate 2) 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.

Notable success has been achieved in the bio-suppression 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 five years resulted in highly significant reduction in *Opisina* population (Sathiamma et al., 2000). Follow up observations revealed that even after three 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).

PRODUCTION AND UTILISATION OF BIOCONTROL AGENTS

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 bio-agents. 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 & predators, which could be released for the management of some major pests on different crop ecosystems.

*Trichogramma* spp. and *Trichogrammatatoidea* spp. are egg parasitoids widely used against the lepidopteran pests infesting sugarcane, paddy and vegetables. They are mass reared on factitious hosts *viz.* *Corcyra cephalonica* Stainton, *Sitotroga cerealella* (Olivier) and *Ephhestia kuehniella* Zeller. Recent studies indicate that the production of *T. chilonis* on eri silkworm *Samia cynthia ricini* eggs is a farmer friendly system (Lalitha et al., 2013) and it could potentially yield trichogrammatids with superior biological attributes.

Biological control through augmentation has gained maximum acceptance among 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 bio-control. Inundative releases of *Isotoma javensis* gave good results in the control of top borer, *Scirpophaga excerptalis* in north India.

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

Production techniques are available for some potential parasitoids like Trichogrammatids, *Leptomastix dactylopii*, *Copidosoma koehleri*, *Telenomus remus*, etc. and predators like *Chrysoperla carnea*, *Scymnus coccivora*, *Pharoscymnus horni*, *Curinus coerules*, *Coccinella septempunctata*, *Cheilomenes sexmaculata*, *Chilocorus nigrita*, *Brumoides surturalis*, *Ischiodon scutellaris*, *Cardiastethus exigus*, etc. (Joshi et al., 1998; Singh et al., 2001; Ballal et al., 2003a; Joshi et al., 2003).

Now potential parasitoids which are amenable to mass production are being reared and marketed by some 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. Trichogrammatids and *Cryptolaemus montrouzieri* are two agents which are widely utilized in India.

**Cryptolaemus montrouzieri**

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 (Mani and Shivaraju, 2016). Some mealybugs have also developed 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 an effective predator on 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). Now commercial insectaries are also procuring 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 & 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. It was effective in suppressing the mealy bugs on citrus, guava, grapes, mulberry, coffee, mango, pomegranate, custard apple, ber etc. and 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 provides information on the pest species (with host plants) against which *C. montrouzieri* was observed to be a promising bioagent.

**Chrysopids**

*Chrysoperla carnea* can be multiplied on the eggs of *C. cephalonica* by adopting a two-step rearing procedure; an initial group rearing procedure and later individual rearing to avoid cannibalism. A monocrotophos tolerant strain of *C. carnea* has been selected by Gujarat Agricultural University, Anand. Attempts have also been made to rear *C. carnea* larvae on semi synthetic diet, which includes the utilization of wastes from other insect production units.

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. The cost of production and application of *C. carnea* @ 1,00,000/ ha is high and hence the focus is on reducing the cost involved in field use through either manipulation of the dosages or reduction in production cost.

**Anthocorids**

An annotated catalogue on Indian anthocorids has been compiled by Ballal *et al.* (2018). In India, very few attempts were made to rear anthocorid predators. Mukherjee *et al.*, (1971) tried a synthetic diet for the rearing of *Xylocoris flavipes* (Reut.). Mass rearing methods have been standardised for four potential anthocorid predators, *Cardiastethus exigus* Poppius (Ballal *et al.*, 2003a), *Blaptostethus pallescens* Poppius (Ballal *et al.*, 2003b) and *X. flavipes* (Reuter) (Ballal *et al.*, 2013) and *Orius tantillus* Motshulsky (Gupta and Ballal, 2006).

The anthocorid species which are now being commercially produced and field utilized in other countries are *Anthocoris nemoralis* (Fabricius) and *Orius* spp. In India, *C. exigus* has been field evaluated against *O. arenosella* and *B. pallescens* against spider mites and thrips. Both the anthocorids have proved to be potential predators for field use (Lyla *et al.*, 2006; Ballal *et al.*, 2009).

**CLASSICAL BIOLOGICAL CONTROL**

To tackle exotic 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.
Plate 1: Some important bioagents for conservation biocontrol

<table>
<thead>
<tr>
<th>Encarsia flavoscutellum Zehntner</th>
<th>Encarsia guadeloupae Viggiani</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aenasius arizonensis (Girault)</td>
<td>Cheilomenes sexmaculata (Fabricius)</td>
</tr>
<tr>
<td>Coccinella septempunctata Linnaeus</td>
<td>Dipha aphidivora (Meyrick)</td>
</tr>
<tr>
<td>Micromus igorotus (Banks)</td>
<td>Peucetia viridana Stoliczka</td>
</tr>
</tbody>
</table>
Plate 2: Some important bioagents for augmentative biocontrol

- *Trichogramma chilonis* Ishii
- *Trichogramma japonicum* Ashmead
- *Chrysoperla zastrowi sillemi* (Esben-Petersen)
- *Goniozus nephantidis* (Muesebeck)
- *Blaptostethus pallescens* Poppius
- *Cryptolaemus montrouzieri* Mulsant
- *Scymnus coccivora* Ramakrishna Ayyar
- *Brumoides suturalis* (Fabricius)
Plate 3: Some important exotic bioagents for classical biological control

- *Acerophagus papayae* Noyes & Schauff
- *Curinus coeruleus* (Mulsant)
- *Trichogramma pretiosum* Riley
- *Cyrtobagous salviniae* Calder & Sands
- *Neochetina eichhorniae* Warner
- *Neochetina bruchi* Hustache
- *Zygogramma bicolorata* Pallister
- *Smicronyx lutulentus* Dietz
<table>
<thead>
<tr>
<th>Crop/Pest</th>
<th>Biotic agents</th>
<th>Dosage per ha</th>
<th>Frequency of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUGARCANE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chilo spp.</td>
<td><em>Trichogramma chilonis</em></td>
<td>50,000</td>
<td>Every 10 days, 8 times starting from 30-day-old crop for shoot borer and 60 days for other borers or during egg laying period</td>
</tr>
<tr>
<td>Pyrilla perpusilla</td>
<td><em>Epiricana melanoleuca</em></td>
<td>2-3 egg masses or 5-7 cocoons in 40 selected spots/ha</td>
<td>The releases to be initiated before the onset of rainy season</td>
</tr>
<tr>
<td>RICE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Scirpophaga incertulas</em> &amp; <em>Cnaphalocrocis medinalis</em></td>
<td><em>Trichogramma japonicum</em> T. <em>chilonis</em></td>
<td>100,000</td>
<td>30, 37 and 44 days after transplanting (DAT)</td>
</tr>
<tr>
<td>COTTON</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helicoverpa armigera, <em>Earias</em> spp., <em>Pectinophora gossypiella</em></td>
<td>T. <em>chilonis</em></td>
<td>1,50,000</td>
<td>Weekly 6 times starting from 40th day after planting or during the egg laying period</td>
</tr>
<tr>
<td>TOBACCO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spodoptera litura</td>
<td><em>Telenomus remus</em></td>
<td>1,20,000</td>
<td>Five times at weekly interval</td>
</tr>
<tr>
<td>COCONUT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opisina arenosella</td>
<td><em>Goniozus nephantidis</em></td>
<td>3,000 adults</td>
<td>Need based or for each generation</td>
</tr>
<tr>
<td></td>
<td><em>Cardiastethus exiguous</em></td>
<td>50 adults/tree</td>
<td>To coincide with egg or freshly hatched larval stage of the pest</td>
</tr>
<tr>
<td>APPLE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eriosoma lanigerum</td>
<td><em>Aphelinus mali</em></td>
<td>1000 adults or mummies / infested tree</td>
<td>Once, as soon as infestation is noticed</td>
</tr>
<tr>
<td>Quadraspidiotus perniciosus</td>
<td><em>Encarsia perniciosi</em></td>
<td>2000 adults / infested tree</td>
<td>Once, in spring</td>
</tr>
<tr>
<td>Cydia pomonella</td>
<td><em>Trichogramma embryophagum</em></td>
<td>2000 adults /tree</td>
<td>Releasing at weekly interval</td>
</tr>
<tr>
<td>CITRUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planococcus citri</td>
<td><em>Leptomastix dactylopii</em></td>
<td>3000 adults</td>
<td>Need based; under expert supervision</td>
</tr>
<tr>
<td>TOMATO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helicoverpa armigera</td>
<td><em>Trichogramma brasiliense</em> T. <em>pretiosum</em> / T. <em>chilonis</em> BioH$_1$</td>
<td>50,000</td>
<td>Weekly interval/6 times from 25th day after transplanting or during egg laying period</td>
</tr>
</tbody>
</table>
Table 2. Biological control of mealy bugs and scale insects utilising *Cryptolaemus montrouzieri*

<table>
<thead>
<tr>
<th>Crop</th>
<th>Species</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>Araucaria</td>
<td><em>Uhleria araucariae</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Brinjal</td>
<td><em>Coccidohystrix insolita</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Crotons</td>
<td><em>Planococcus minor</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Ficus</td>
<td><em>Pulvinaria psidii</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Hibiscus</td>
<td><em>Aphis gossypii</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Jacaranda</td>
<td><em>Saissetia coffeae</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Jasmine</td>
<td><em>Pseudococcus longispinus</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Mulberry</td>
<td><em>Insignorthezia insignis</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Mussaenda</td>
<td><em>Megapulvinaria maxima</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Neem</td>
<td><em>Coccus viridis</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Sapota</td>
<td><em>Planococcus citri</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Tomato</td>
<td><em>Planococcus citri</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Ber</td>
<td><em>Nipaecoccus viridis, P. lilacinus, P. citri M. hirsutus and Drepanococcus chiton</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Chow-chow</td>
<td><em>P. lilacinus</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Citrus</td>
<td><em>Planococcus citri</em> and <em>Nipaecoccus viridis</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Coffee</td>
<td><em>Planococcus spp.</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Custard apple</td>
<td><em>M. hirsutus, P. citri, P. lilacinus, F. virgata and N. viridis.</em></td>
<td>Karnataka and Andhra Pradesh</td>
</tr>
<tr>
<td>Grapevine</td>
<td><em>Maconellicoccus hirsutus</em> and <em>Planococcus citri</em></td>
<td>Karnataka and Andhra Pradesh</td>
</tr>
<tr>
<td>Guava</td>
<td><em>Pulvinaria psidii, Aphis gossypii, Drepanococcus chiton, Ferrisia virgata, Planococcus citri and P. lilacinus</em></td>
<td>Karnataka and Tamil Nadu</td>
</tr>
<tr>
<td>Mango</td>
<td><em>Pulvinaria polygonata, Ferrisia virgata, Planococcus citri, Rastroccus iceroyoides and R. invadens</em></td>
<td>Karnataka</td>
</tr>
<tr>
<td>Pomegranate</td>
<td><em>Siphoninus phillyreae Maconellicoccus hirsutus, Planococcus citri, P. lilacinus, Ferrisia virgata and Nipaecoccus viridis</em></td>
<td>Karnataka</td>
</tr>
</tbody>
</table>

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 exotic natural enemies in several countries. India is rated as one of the top 10 countries in the world in the area of biological control. Where success has been achieved in classical biological control, the underlying ecological mechanisms are not always clear.

Exotic parasitoids that have successfully established in our country (Plate 3) include the encyrtids *Encarsia*
perniciosi and Aphytis diaspidis for control of San Jose scale, Quadraspidiotus perniciosus and similarly, Leptomastix dactylopii against citrus mealybugs.

Leptomastix 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 per cent parasitism in Himachal Pradesh. A. diaspidis in combination with E. perniciosi gave 86.5 per cent 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 per cent. In Kashmir, releases of E. perniciosi and Aphytis proclia resulted in an increase of parasitism from 8.9 to 64.3 per cent. 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).

The spiraling whitefly, Aleurodicus disperses, 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. disperses (Ramani et al., 2002).

The invasive papaya mealybug Paracoccus marginatus, an alien mealybug native to Mexico, was first reported on papaya in Coimbatore, and soon it spread to neighboring districts infesting cassava (tapioca), mulberry, teak and more than 100 other plant species. Papain, sago and silk industries were significantly affected by this pest. ICAR–NBAIR with help from the United States Department of Agriculture (USDA) imported three natural enemies of the papaya mealybug, namely, Acerophagus papayae, Anagyrus loecki and Pseudleptomastix mexicana, from the laboratory of Animal and Plant Health Inspection Services (APHIS) at Puerto Rico. A large-scale production technology was developed and one of the parasitoids A. papaya was distributed to all the states which reported infestation by the papaya mealybug. Within a period of six months, the papaya mealybug was controlled successfully. The total economic benefit over five years was estimated to be $ 1,340 million. It is estimated that an annual saving of Rs 1,623 crores has accrued to the farmers in Tamil Nadu, Karnataka and Maharashtra.

MANAGEMENT OF INVASIVES THROUGH CONSERVATION

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* were recorded as potential predators of SWA in nature. Since natural enemies were found to control the woolly aphid effectively, farmers were advised not to apply chemical pesticides. In areas where chemicals were not applied, the natural enemies multiplied rapidly and devoured the woolly aphid, thus preventing outbreaks.

Invasive rugose spiraling whitefly (RSW) *Aleurodicus rugioperculatus* Martin (Hemiptera:Aleyrodidae) was found infesting coconut, banana, coconut, banana, custard apple and several ornamental plants in Tamil Nadu, Andhra Pradesh and Kerala. Several natural enemies were recorded on this pest and maximum parasitism was recorded by *Encarsia guadeloupae* Viggiani. Through recommendations on a non-chemical pesticidal approach, the pest population has drastically reduced in most of the areas (Selvaraj et al., 2017).

**SUPERIOR STRAINS OF NATURAL ENEMIES**

In a successful attempt to bridge the gap between research and commerce, a strain of *T. chilonis* ‘endogram’ with physiological tolerance to 0.07% of endosulfan was developed for control of cotton bollworm (Jalali et al., 2006; Ballal et al., 2009). This strain was commercialized and in three years, 29700 hectares of cotton and vegetables crops were treated with endogram in 6 different states. This strain was further developed for multiple tolerances to the recommended dosages of monocrotophos and fenvalerate. A strain of *T. chilonis* which can tolerate a temperature of 36º C was also developed, which could be utilized in states like Punjab and Tamil Nadu. High host searching strains of *T. chilonis*, *T. japonicum*, *T. achaeeae* and *T. bactrae* were also developed which were more efficient in field situations.

**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. As per “Infobase” (Biswa et al., 2000) and Singh (2002), there are 128 organisations producing bio-agents. However, though microbial biopesticides are available commercially in India, very few companies are producing macrobials.

Biological control workers have to face several major 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 lack of: a) long term storage techniques for the alternate laboratory host insect *Corcyra cephalonica* and also for Tricho cards, b) mechanized production and application technology of parasitoids and predators, c) effective in-vitro mass production techniques for natural enemies on artificial diets, d) techniques that prevent selection pressures and behavioural changes leading to genetic deterioration of the mass-produced natural enemies,
and loss of vigour/effectiveness and f) good standards to measure the quality of the bioagents and their performance. The hurdles faced during rearing also include problems faced in: a) male-biased sex-ratio in the laboratory cultures, b) maintenance of cultures during summer and winter due to unfavourable temperature and humidity conditions, c) cannibalism in chrysopids and in some coccinellid larvae which necessitates individual rearing d) in vivo rearing of predators as it necessitates continuous production of host insects and host plants, e) Bracon and mites in Corcyra culture, f) microbial contaminants in laboratory host insect cultures g) higher costs involved in preparing semi-synthetic diets

Some of the above issues have been addressed through research at NBAIR. Long term storage techniques for host insects and biocontrol agents are of great relevance for commercial acceptance of biocontrol technologies. Eggs of C. cephalonica stored for 20 days (10 days prior to UV and 10 days post UV) were effectively parasitized by T. chilonis with upto 88.4% parasitism and when stored for 30 days, parasitism ranged 70-80% (Ghosh and Ballal, 2017a). Jalali et al. (2007) devised a method of vacuum packing UV irradiated C. cephalonica eggs. Successful long term storage (up to 95 days) of T. chilonis strains was enabled through a novel technology of diapause induction (Ghosh and Ballal, 2017b; 2018). Rearing structures and units have been devised and protocols have been standardized to maintain optimum temperature and humidity and hygienic conditions, prevent cannibalism and entry of hypers, disease and contaminants into the rearing facilities, mechanical collection of moths and simulate field conditions. For rearing some of the parasitoids like Encarsia spp. and predatory mites, rearing of host insects / phytophagous mites on host plants is essential. Methods have been devised to either re-distribute the bioagents from areas of occurrence to new areas and rearing of predatory mites on astigmatid mites, thus trying to minimize the cost involved in maintaining host plants continuously in polyhouses. Though in-vitro mass production techniques have been attempted, they may not be feasible in Indian conditions considering the cost involved. In order to prevent biodeterioration of cultures due to continuous laboratory rearing, the stage at which rejuvenation has to be done with wild cultures has been identified. Studies have also clearly indicated the importance of maintaining quality parameters in mass reared insects (Ballal et al., 2001b, c; 2005).

CONCERNS, CONSTRAINTS & FUTURE THRUSTS

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. 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. Global warming has now been accepted as a serious threat to our natural and agroecosystems. 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 and on the natural enemies themselves. Interactions between transgenic crops and biological control species have also to be considered.

In classical biocontrol, there is a concern whether the chosen exotic bioagent would be able to provide sufficient control. A long debated issue is also whether one, a few or many species of natural enemies should be released against invasive pests (Ehler, 1990). Some evidences were brought forth on the competitive
exclusion of introduced bioagents by the indigenous bioagents (Ehler and Hall, 1982). Classical biological control is ideally expected 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. Nontarget impacts to plants or insects from biocontrol agents are of great concern to conservation biologists, environmentalists, and federal agencies. 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 thus more research emphasis has been placed on parasitoid species (Goldson et al., 1994).

Evans (2016) states that biodiversity affects ecosystem functioning in general and classical biological control in particular. In classical biological control, the question is whether we should build a more diverse or a less diverse natural enemy community to attack the invasive pest in its new geographic range. Some studies indicate that successful suppression of target pest occurs through integrated contributions of multiple introduced species termed as “cumulative stress” (Denoth et al., 2002). Alternately, in several cases, a single introduced species of natural enemy has succeeded in managing the pest (Myers et al., 1989). Still another approach termed as the “lottery approach” is to release multiple species hoping that the “best” species or the combination of species would be sorted out in the field (Ehler and Hall, 1982). However, this approach has come under scrutiny due to concerns regarding non-target effect and negative interactions among competing natural enemies. The complementary of natural enemies was observed in the case of two seed feeding insects – a fly Urophora quadrifasciata (Meigen) and a weevil Larinus minutus Gyllenhal which together inflicted greater seed destruction of the invasive squarrose knapweed in Utah desert (Evans, 2016). Complementarity between natural enemies becomes clear and consistent when temporal and spatial scales are expanded.

Though increased species richness generally strengthens biological control, negative effects have been reported in some cases. Jonsson (2017) have tried to bring out the factors which are responsible for the different outcomes. Resource partitioning, facilitation and positive selection effects are the factors which link species richness to increased biological control, while factors like intraguild predation, behavioral interference and negative selection effects are responsible for greater enemy diversity leading to weakened prey suppression.

Research at NBAIR indicated that combinations of biological control agents can enhance the overall suppression of pests on crops, for instance, for the management of brinjal fruit and shoot borer and brinjal mealy bug, T. chilonis and C. montrouzieri can be effectively utilized. Northfield et al (2010) evaluated their experiments with a model where they could demonstrate that through niche partitioning, two predators could perform in a complementary manner and could suppress aphid population infesting collard plants. The compatibility of anthocorid and geocorid predators with T. chilonis was proved by Gupta and Ballal (2007) and Varshney and Ballal (2017). Cryptolaemus montrouzieri was observed to be compatible with parasitoids Anagyrus dactylopii and Aeniasius advena for management of grape mealy bug (Mani et al., 1990). However, interaction studies between parasitoids Chelonus blackburni Cam and Copidosoma koehleri Blanch. (Ballal et al., 1989), Cotesia kazak Telenga and Hyposoter didymator (Thunb.) (Jalali
et al., 1988) and Campoletis chlorideae Uchida and Eriborus argenteopilosus (Cameron) (Bajpai et al., 2006), indicated that when one of the parasitoids emerged as the dominant one, it is advisable not to release them together against the target pest. Finke and Snyder (2008) demonstrated complementarity by directly manipulating the niche breadth of natural enemy species. This can be done through manipulation of niche overlap or spatial niche partitioning.

Intrinsic and extrinsic ecological factors are known to moderate the effect of natural enemy diversity. Biological practitioners can predict the effect of natural enemy diversity on biological control if they can understand the traits of the natural enemies (e.g., body size, foraging mode, microhabitat use, diet breadth, phenology, diel activity and relative abundance) and the extrinsic factors which include prey traits (life cycle, diversity, density, patchiness) and environmental variables (plant composition, habitat complexity, host plant taxon, temperature, spatial and temporal scale). Within a species, the occurrence of both active and sedentary individuals can increase prey suppression (Roytze and Pruitt, 2015). In the case of a sedentary target pest, roaming natural enemies are expected to provide effective control. “Sit and wait” predators may not always encounter the prey and is expected to function more as an intraguild predator (Roseinheim and Corbett, 2003).

The general inferences on the factors affecting the relationship between biodiversity and biocontrol can vary depending on the context. A high diversity in the microhabitat use of the natural enemies can be advantageous only if the pest also uses a diversity of microhabitats (Schmitz and Barton, 2014). Environment variables can also influence the relationship. The differences in body size of the natural enemies, generally considered as a disadvantage can prove to be advantageous for biological control of holometabolous pests who have size variations during development or while tackling multiple pests of varying sizes (Wilby et al., 2005).

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. Future biocontrol attempts must consider climate variables in evaluating long-term effectiveness. Biological control scientists are expected to provide management professionals with sustainable and effective tools with which to manage the relentless pressure of invasive species and indigenous pest outbreaks on natural and agricultural ecosystems.

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DR. (Ms.) CHANDISH R. BALLAL, Director, ICAR-National Bureau of Agricultural Insect Resources, Bengaluru received her B Sc, M Sc and M Phil Degrees from Calicut University. She was a Merit Scholarship holder throughout her education and a University first rank holder for her M Phil degree. Her first posting as ICAR scientist was in the Indian Institute of Horticultural Research in 1985 and later moved on to the Project Directorate of Biological Control during the formative years of PDBC, which has now been upgraded as ICAR-National Bureau of Agricultural Insect Resources. She was the HOD of Division of Insect Ecology from 2013 to 2016 and currently is the Director of ICAR-NBAIR 2016 onwards. She has always laid a lot of emphasis on environmental safety and sustainability by focusing her research efforts on conservation of biodiversity and “Biological control” a non-chemical mode of insect pest management. She has standardized continuous and effective production technologies for beneficial insects, which are being widely adopted by commercial units, researchers and students. She holds the largest live insect repository in Asia, with 117 different insect cultures. The prompt and continuous supply of quality live insect cultures made and production protocols developed by her are valuable services to the student community, bio-control researchers and commercial insectaries. By interacting with farmers and conducting demonstration trials in farmers’ fields, she has created confidence in farmers on the non-chemical mode of pest management. She has handled around 40 research projects and has more than 230 research publications to her credit. She has received international travel grants from DST, IOBC, CSIR, CABI, ICAR and Beijing Academy of Sciences to present her research papers in international conferences in India, Greece, China, Sri Lanka and USA. She is an elected fellow of several Professional Societies and is the recipient of several awards and recognitions including Prof. T N Ananthakrishnan Award 2006, Dr Sithanantham Award 2010-11, NBAIR scientific excellence Award 2015, Dr S P Singh Biocontrol Lifetime Achievement Award 2016 and the prestigious ICAR Panjabrao Deshmukh Outstanding Woman Agricultural Scientist Award 2015. Throughout her career, by way of training of stake-holders, publications related to biodiversity & biocontrol, guidance provided to students, farmer interactions and supply of quality biological control agents, she has made concerted efforts to create awareness on the importance of a healthy environment and to popularise the concept of biological control for pest management.