1

Conventional and Biotechnological Approaches for Pest Management: Potential and Limitations

H.C. Sharma

Abstract

There has been a tremendous change in the pest spectrum and the pest management practices over the past five decades. Several insect species have attained the status of a major pest, while insect resistance to insecticides and pest resurgence have been observed on a large scale as a result of indiscriminate use of pesticides. Over the past five decades, there has been a qualitative shift in pest management tactics from cultural and mechanical control and use of synthetic insecticides to greater use of microbials, natural plant products, selective insecticides, and genetically modified insect-resistant crops. Strategies for pest management, in general, have been dominated by the search for a 'silver bullet' products / interventions to minimize the losses due to insect pests. However, therapeutic interventions into biological and ecological systems provide only a short-term relief, and the effects of such interventions are neutralized by the countermoves within the biological and ecological systems. Long-term answers to pest problems can only be sought by re-structuring and managing ecosystems in a way that enhance the ability of in-built mechanisms to resist insect damage, while the therapeutic tactics serve as a back up to the natural regulatory processes. There is a need to exploit the modern tools of biotechnology for pest management to increase the efficacy of biopesticides and natural enemies, and increase the levels of host plant resistance to insects through genetic engineering and gene pyramiding for sustainable crop protection and environment conservation.

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru – 502 324, Andhra Pradesh, India.

**Corresponding author*: Email: h.sharma@cgiar.org

INTRODUCTION

Advances in crop improvement have led to "Green Revolution" becoming one of the scientifically most significant events in the history of mankind (Swaminathan 2000). Grain production has shown a remarkable increase from 1950 to 1980, while only a marginal increase has been recorded from 1980 onwards. However, the world population will cross 7.5 billion by 2020, and nearly 1.2 billion people live in a state of absolute poverty (Pinstrup-Andersen and Cohen 2000). While the human population is increasing rapidly, the arable land for food production is decreasing at a fast rate (Fig. 1), and such a decrease will be greater in the developing countries, where most of the increase in population will occur. This has necessitated production of more food on the existing arable land. One of the practical means of increasing crop production is to minimize the pest-associated losses (Sharma and Veerbhadra Rao 1995), currently estimated at 14% of the total agricultural production (Oerke 2006). Nearly 30 to 50% of the actual crop productivity is lost due to insect damage (Fig. 2). Crop losses due to insect pests, diseases, and weeds have increased from 34.9 to 42.1% over the past 50 years, despite the intensification of pest control measures. There are additional costs in the form of pesticides applied for pest control, valued at US$10 billion annually. The conventional approach of killing the pest insects with chemicals has been the dominant strategy for pest management, although considerable efforts have been made to develop alternative technologies for pest management. Much of the effort has been directed towards using modern chemistry and molecular technologies to replace the hazardous chemicals, and the non-toxic biological products. Massive application of pesticides to minimize the losses due to insect pests, diseases, and weeds has resulted in adverse effects on the beneficial organisms,

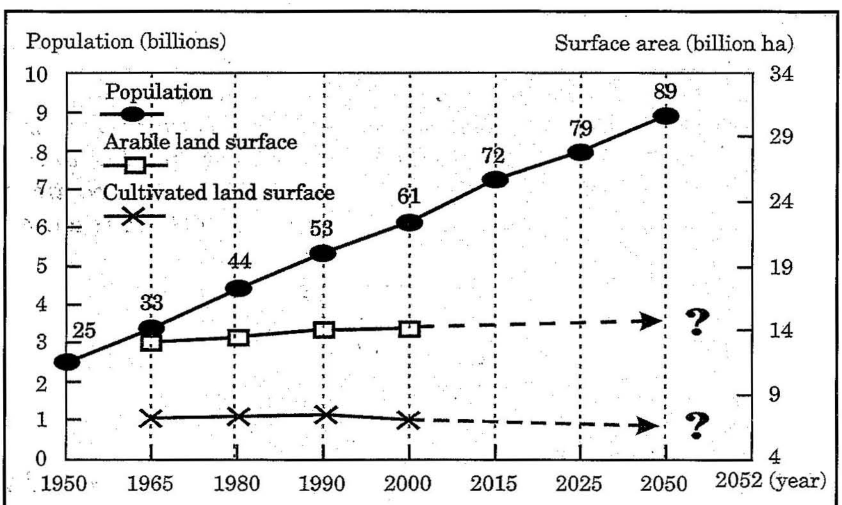


Fig. 1: Population increase and availability of land for food production.

pesticide residues in the food and food products, and environmental pollution. This has necessitated the use of selective insecticides, compounds with low persistence, and an increase in emphasis on integrated pest management (IPM). Although pesticide use in agriculture has resulted in a considerable reduction in pest-associated losses and stabilized crop production, there is an increasing concern regarding the adverse effects of pesticides on the environment. Although the benefits to agriculture from the pesticide use to prevent insect-associated losses cannot be overlooked, there is a greater need to develop alternative technologies, which would allow a rational use of pesticides for sustainable crop protection.

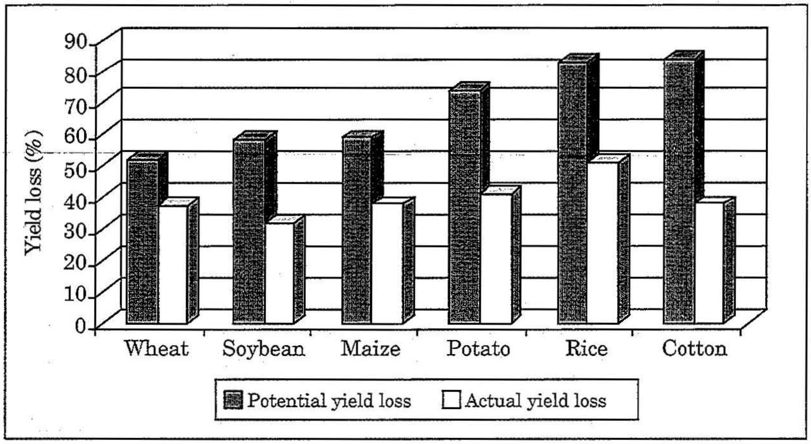


Fig. 2: Extent of losses due to insect pests in major crops worldwide (Oerke 2006).

INSECT PEST PROBLEMS IN AGRICULTURE: THE CHANGING SCENARIO

Chronic pest problems

There are several insect pests, which are difficult to control even with the application of insecticides, and continue to cause widespread damage across seasons and geographic regions. Cotton bollworms (*Heliothis*, *Helicoverpa*, *Pectinophora*, and *Earias*), plant hoppers (*Pyrilla*, *Nilaparvata*, *Nephotettix*, *Peregrinus*, *Empoasca*, and *Amrasca*), whiteflies (*Bemisia*, *Aleurocanthus*, and *Aleurodes*), stem borers (*Chilo*, *Ostrinia*, *Sesamia*, *Diatraea*, *Ascigona*, and *Scirpophaga*), scale insects (*Eriosoma*, *Planocuccus*, and *Phenacoccus*), diamond back moth (*Plutella*), fruit flies (*Dacus* and *Bactrocera*), white grubs (*Holotrichia*, *Anomala*, and *Phyllophaga*), gypsy moth (*Lymantria*), Colorado potato beetle (*Leptinotarsa*), Hessian fly (*Mayetiola*), sorghum shoot/stem flies (*Atherigona* and *Ophiomyia*), aphids (*Aphis*, *Schizaphis*, *Melanaphis*, and *Acyrthosiphon*), armyworms and hairy caterpillars (*Mythimna*, *Spodoptera*, and *Amsacta*), and termites and locusts continue to be the chronic pest problems (Sharma and Veerbhadra Rao 1995; Sharma 2009). Although considerable efforts have been made to devise strategies to control these pests, they still continue to inflict considerable damage in different crops and cropping systems in various parts of the world.

Emerging pest problems

Introduction of high-yielding varieties, increased use of fertilizers and irrigation, changes in crops and cropping patterns, and indiscriminate use of pesticides have changed the pest spectrum. Until 1950s', insect pests were not of major concern in crop production. There were some instances of pest outbreaks, particularly grasshoppers and locusts, pink bollworm, *Pectinophora gossypiella* (Saunders), cotton boll weevil [*Anthonomus grandis* (Boh.)], leaf defoliators and stem borers. There have been both qualitative and quantitative changes over the past five decades in insect pest problems and their management (Sharma and Veerbhadra Rao 1995; Norton et al. 2005). Intensive and extensive cultivation of high yielding varieties to increase food grain production and indiscriminate use of pesticides have resulted in emergence of many pest problems, in addition to development of resistance to insecticides in many insect species. Cotton bollworm/legume pod borer, *Helicoverpa armigera* (Hubner) emerged as a major pest of cotton in mid-seventies. Previously, this insect was regarded as a pest of chickpea and tomato in India, and was commonly known as gram pod borer or tomato fruit borer. Now, it is known to cause heavy losses in cotton, legumes, cereals, vegetables, and fruit crops (Sharma 2005). Similarly, cotton white fly, *Bemisia tabaci* Genn. has emerged as a major pest of cotton and several other crops since mid-eighties due to widespread use of synthetic pesticides (Anderson and Morales 2005). Tobacco caterpillar *Spodoptera litura* (F.) has emerged as a serious pest on several crops in South-Central India, particularly on transgenic cotton. Recently, coconut mite, *Aceria guererronis* (Keifer) has become a major pest of coconut crop. Severity of damage by brown planthopper, *Nilaparvata lugens* (Stal.), rice gall midge, *Orseolia oryzae* (Wood-Mason), sugarcane pyrilla, *Pyrilla perpusilla* Walker, diamond back moth, *Plutella xylostella* (L.), and mango fruit fly, *Bactrocera dorsalis* (Hendel) has increased tremendously, and pose a serious problem for sustainable crop production and food security. Some minor insects such as white-backed planthopper, *Sogatella furcifera* (Horvath) in rice, coffee stem/ berry borers (*Xylotrechus, Monochamus,* and *Dirphya*), and soybean girdle beetle, *Oberea brevis* Gah. have emerged as major pests. The serpentine leaf miner, *Liriomyza trifolii* Burgess has emerged as a serious pest of several crops worldwide over the past two decades.

Insect resistance to insecticides

Many species of insect pests have also developed resistance to insecticides, and 645 cases of resistance have been documented until 1996 (Myers 1999). Maximum reports of resistance development pertain to organophosphates (250), followed by synthetic pyrethroids (156), carbamates (154), and others (including chlorinated hydrocarbons) (85). Maximum numbers of insects and mites showing resistance to pesticides have been recorded in vegetables (48), followed by those infesting fruit crops (25), cotton (21), cereals (15), and ornamentals (13). *Helicoverpa armigera* has shown resistance to several groups of insecticides in cotton, tomato, chilies, sunflower, groundnut, pigeonpea, and chickpea (Kranthi et al. 2002). The cotton whitefly, *B. tabaci* has shown resistance to insecticides in cotton, brinjal, and okra; while tobacco caterpillar, S. *litura* has been found to be resistant to insecticides on cotton, cauliflower, groundnut, and tobacco. Green peach and potato aphid, *Myzus persicae* (Sulzer), mustard aphid, *Lipaphis erysimi* (Kalten.), and diamond back moth, *P. xylostella* have also been found to exhibit resistance to various insecticides (Shelton et al. 1993). Development of resistance to insecticides has necessitated the application of higher dosages of the same pesticide or increased number of pesticide applications.

PEST MANAGEMENT COMPONENTS: POTENTIAL AND LIMITATIONS

Cultural practices, natural enemies, bio-pesticides, natural plant products, semiochemicals, and pest-resistant varieties offer a potentially safe method of managing insect pests. Unlike synthetic pesticides, some of these technologies (insect-resistant varieties, natural enemies, *Bacillus thuringiensis* (*Bt*) Berliner, nucleopolyhedrosis viruses (NPVs), entomopathogenic fungi, and nematodes) have the advantage of replicating themselves or their effect in the field, and thus, have a cumulative effect on pest populations. Despite being environment friendly, the alternative technologies have some serious limitations such as: i) mass production, ii) slow rate of action, iii) cost effectiveness, iv) timely availability, and v) limited activity spectrum. Some of the natural enemies such as *Trichogramma*, *Cotesia*, *Bracon*, *Chrysoperla*, and *Coccinella*; and the biopesticides such as *Bt*, and NPVs are being produced commercially. Strains of *Pseudomonas, Beauveria,* and *Metarhizium* are also effective in controlling insect pests. Natural plant products from neem, *Azadirachta indica* A. Juss., custard apple, *Annona squamosa* L., and *Pongamia pinnata* (L.) Pierre. have also been recommended for pest control.

Several varieties with resistance to insects have been developed, but very few are cultivated by the farmers on a large-scale because of lack of sustained seed supply (Sharma and Ortiz 2002). However, many of alternative technologies are not as effective as the synthetic insecticides, and there is no sustained effort by the industry and the government agencies to promote their use, and as a result, have not been adopted widely by the farming community on a large scale. Therefore, there is an urgent need to:

- Improve mass production and delivery system of natural enemies.
- Improve bioefficacy and formulations of bio-pesticides and natural plant products.

- Production and distribution of seeds of insect-resistant cultivars.

Management of insect pests on high-value crops such as cotton, vegetables and fruits, and sugarcane relies heavily on insecticides, often to the exclusion of other methods of pest control (Sharma and Veerbhadra Rao 1995; Norton et al. 2005). With an increasing restraint on insecticide use due to development of resistance in insect populations and environmental contamination, integration of several management techniques has become necessary to reduce the reliance on insecticides, and prolong the utility of important molecules. In order to overcome the toxic and chronic effects of pesticides and avoid pest resurgence, intensive research efforts are needed to develop a balanced program for IPM.

Biological control

A renewed interest has been generated in using biological control because of the hazards associated with pesticide use. The term biological control has been used in a broad sense to encompass natural enemies, biopesticides, pheromones, sterile insect technique, etc. However, more prevalent use of this term is restricted to the use of natural enemies to manage pest populations in field, forestry, and greenhouse systems. There are some spectacular examples of the success of biological control through importation and release of natural enemies, particularly in the perennial ecosystems. However, this approach has not shown the same level of success in annual crops because of lack of concerted research efforts to identify the factors that determine the success or failure of programs aimed at biological control of insect pests. Efforts for mass rearing and release technologies have received a lot of attention, and these work no more differently than therapeutic treatments, and it is simply an extension of the treat-the-system paradigm (Lewis et al. 1997), and in principle, the natural enemies are used as biological pesticides.

Natural enemies

Trichogrammatids, ichneumonids, braconids, chalcids, and tachinids have been used extensively in inundative releases. The most important and widely used parasitoids for biological control of insects are the egg parasitoids such as *Trichogramma, Chelonus,* and *Telenomus.* The larval parasitoids such as *Cotesia, Apentales, Encarsia, Gonatocerus, Campoletis, Bracon, Enicospilus, Palexorista, Carcelia, Sturmiopsis,* etc. have also been used for biological control of insects in several countries. In general, predators have received much less attention than parasitoids as bio-control agents. They exercise greater control on pest populations in a diverse array of crops and cropping systems. The most common predators include *Chrysoperla, Nabis, Geocoris, Orius, Polistes,* and the species belonging to Pentatomidae, Reduviidae, Coccinellidae, Carabidae, Formicidae, and Araneida. Some of the predators have also been used in augmentative release studies, notably *Chrysoperla carnea* (Stephen). Although effective in large numbers, the high cost of large-scale production precludes their economic use in biological control (King and Coleman 1989), and such programs need to be backed by the government agencies over a long period of time. Much less emphasis has been given on how the natural enemies function, and how to promote their activity from one season to another, and the spread from one region to another. There is a need to understand, promote, and maximize the effectiveness of the indigenous natural enemy populations, and establishment and spread of natural enemies that have been released into the newer eco-systems.

System diversification to increase the effectiveness of natural enemies

Major improvements in biological control of insect pests through natural enemies can be made through habitat management. Increasing genetic diversity has been proposed as a means of augmenting natural enemy populations. However, the response of natural enemies to genetic diversity varies across crops and cropping systems (Andow 1991). Hedgerows, cover crops, and weedy borders provide nectar, pollen, and refuge to the natural enemies. Mixed planting and provision of flowering plants at the field borders can increase habitat diversity, and provide more effective shelter and alternative food sources to predators and parasites. Inter- or mixed-cropping, which involve simultaneous growing of two or more crops on the same piece of land are some of the oldest and most common cultural practices in tropical countries for risk aversion and pest management. Increasing genetic diversity also helps to increase the abundance and effectiveness of generalist predators (Sunderland and Samu 2000; Schmidt et al. 2004). Some natural enemies may be more abundant in polycultures because of greater availability of nectar, pollen, and diversity of prey (Bugg et al. 1987) for a longer period of time (Topham and Beardsley 1975). Populations of coccinellid beetles (*Coccinella transversalis* Fab. and *Adalia bipunctata* L.), lacewings (*Chrysopa* spp.), reduviid and pirate bugs [*Coranus triabeatus* (Hozwath)], and spiders (*Lycosa* spp. and *Araneus* spp.) have been found to be greater in maize - cowpea intercrop than on cotton alone. Greater numbers of *Geocoris* spp. and other predators have been recorded on knotweed than on other weed species, because of the availability of floral nectar and alternate prey (Bugg et al. 1987). The predatory mite, *Metaseiulus occidentalis* (Nesbitt) abundance has been found to be greater in plots adjacent to alfalfa intercropped in cotton (Corbett and Plant 1993), while mulching of soil surface with crop residue increases the abundance of generalist predators (Altieri et al. 1985; Schmidt et al. 2004), and reduces insect damage to crops.

Compatibility of host plant resistance with natural enemies

Varieties with moderate levels of resistance that allow the pest densities to remain below economic threshold levels (ETLs) are best suited for use in IPM in combination with natural enemies. Restless behavior and prolonged developmental period of the immature stages on the resistant varieties increases the susceptibility of the target pests to the natural enemies (Sharma et al. 2003). The use of insect-resistant varieties and biological control brings together two unrelated mortality factors, which reduce the pest population's genetic response to selection pressure from plant resistance and the natural enemies. Acting in concert, they provide a density-independent mortality at times of low pest density, and density-dependent mortality at times of high pest density (Bergman and Tingey 1979). Physico-chemical characteristics of the host plants also play an important role in host specificity of both the insect hosts and their parasitoids (Sharma et al. 2003). Host plant exercises a tremendous effect on the activity and abundance of natural enemies, *e.g.* average rates of parasitism of *H. armigera* eggs (mainly by *Trichogramma* spp.) have been found to be 33% on sorghum, 15% on groundnut, and 0.3% on pigeonpea, while little or no parasitism was observed on chickpea (Pawar et al. 1986). Therefore, due care should be taken to select host plants and the parasitoid species while planning for biological control of insect pests.

Entomopathogenic bacteria

Several entomopathogenic bacteria play a major role in controlling insect pests under natural conditions. Formulations based on *B. thuringiensis* have been marketed since 1950s'. There are 67 registered *Bt* products with more than 450 formulations. The major boost to the production and use of *Bt* products came with the discovery of HD-1 strain of *Bt* subspecies *kurstaki,* which is effective against a large number of insect species (Dulmage 1970). Several commercial products such as Thuricide®, Dipel®, Trident®, Condor®, and Biobit® are being marketed worldwide. There are several subspecies of this bacterium, which are effective against lepidopteran, dipteran, and coleopteran insects. Formulations based on *Bt* account for nearly 90% of the total biopesticide sales worldwide (Neale 1997), with annual sales of nearly US$90 million (Lambert and Peferoen 1992). *Bacillus israeliensis* has been used extensively for the control of mosquitoes. Narrow host range, necessity to ingest the *Bt* toxins by the target insects, ability of insect larvae to avoid lethal dose of *Bt* by penetrating into the plant tissue, inactivation by sunlight, and effect of plant surface chemicals on its toxicity limit its widespread use in crop protection (Navon 2000).

Baculoviruses

Baculoviruses are regarded as safe and selective pesticides. They have been used against many insect species worldwide, mainly against lepidopteran insect pests. The NPVs exist as populations in nature, with a wide variation in virulence. Movement within and from soil is basic to the long-term survival and effectiveness of NPVs. The NPVs have amenalistic interactions with other biotic agents. Their use and effectiveness is highly dependent on the environment (Fuxa 2004). The NPVs can be used for the control of some difficult to control insect pests such as *H. armigera* (Pokharkar et al. 1999). The most successful examples have been the use of nuclear polyhedrosis virus of soybean caterpillar, *Anticarcia gemmatalis* (Hubner) and of

Heliothis/Helicoverpa (Moscardi 1999). Narrow host range, slow rate of insect mortality, difficulties in mass production, stability under sunlight, and farmers' attitude have limited the use of NPVs as commercial pesticides. Addition or tank mixing of chemical pesticides and genetic engineering can be used to overcome some of the shortcomings of *baculoviruses*. Much remains to be done to develop effective formulations of *baculoviruses* for effective control of insect pests.

Entomopathogenic fungi

Entomopathogenic fungi have been recognized as important natural enemies of insect pests. Species pathogenic to insect pests are *Metarhizium anisopliae* (Metsch.), *M. flavoviride* (Metsch.), *Nomuraea rileyi* (Farlow) Samson, *Beauveria bassiana* (Balsamo), and *Paecilomyces farinosus* (Holm ex Gray) Brown & Smith (Hajeck and St-Leger 1994; Saxena and Ahmad 1997). For commercial production, a solid-state fermentation system may be more effective. Adhesion of fungal spores to host cuticle and their germination is a pre-requisite for efficacy of fungal pathogens. High relative humidity (>90%) is required for germination of fungal spores, and is a big handicap in the widespread use of entomopathogenic fungi. However, special formulations in oil can overcome this problem by creating high humidity around the spores enabling entomopathogenic fungi to function under dry conditions (Bateman et al. 1993).

Entomopathogenic nematodes

Entomopathogenic nematodes of the genera *Steinernema* and *Heterorhabditis* have emerged as excellent candidates for biological control of insect pests. Entomopathogenic nematodes are associated with the bacterium, *Xenorhabdus*, and are quite effective against a wide range of soil inhabiting insects. The relationship between the nematodes and the bacterium is symbiotic because the nematodes cannot reproduce inside the insects without the bacterium, and the bacterium cannot enter the insect hemocoel without the nematode and cause infection (Poinar 1990). Broad host range, virulence, safety to nontarget organisms, and effectiveness has made them ideal biological control agents (Georgis 1992). Liquid formulations and application strategies have allowed nematode based products to be quite competitive for pest management in high value crops. Entomopathogenic nematodes are generally more expensive to produce than the insecticides, and their effectiveness is limited to certain niches and insect species. There is a need to improve culturing techniques, formulations, quality, and the application technology to overcome the effectiveness of entomopathogenic nematodes for pest management.

Cultural practices

The need for ecologically sound, effective, and economic methods of pest control has prompted renewed interest in cultural methods of pest control.

The merit of many of the traditional farm practices has been confirmed by learning, "Why farmers do what they do?" But some practices, still remain to be thoroughly investigated, and understood. A number of cultural practices such as selection of healthy seeds, synchronized and timely sowing, optimum spacing, removal of crop residues, optimum fertilizer application, and regulation of irrigation are helpful in minimizing pest incidence and crop loss.

Timely sowing

Sowing time considerably influences the extent of insect damage. Normally, farmers plant with the on-set of rains. Synchronous and timely/early sowing of cultivars with similar maturity over large areas reduces population build up and damage by insect pests. Early and uniform sowing of sorghum over large areas has resulted in reducing the damage by shoot fly, *Atherigona soccata* (Rond.) and sorghum midge [*Stenodiplosis sorghicola* (Coquillett)] in India. The traditional practice of using a high seeding rate in Africa helps to maintain optimum plant stand and reduce insect damage in cereals (Sharma 1985).

Fertilizer use

The extent and nature of fertilizer application also influence the crop susceptibility to insects. In some instances, high levels of nutrients increase the level of insect resistance, while in others, they increase the susceptibility to insects. An increase in nitrogenous and phosphatic fertilizers decreases shoot fly, *A. soccata* and spotted stem borer, *Chilo partellus* (Swinhoe) infestation in sorghum (Chand et al. 1979), possibly by increasing plant vigor. Application of potash decreases the incidence of top shoot borer, *Scirpophaga excerptalis* (Walker) in sugarcane. High levels of nitrogen lead to greater damage by the cotton jassid, *Amrasca biguttula biguttula* Ishida. A change in nutrient supply also affects the resistance to greenbug, *S. graminum* in sorghum (Schweissing and Wilde 1979). Increase in nitrogen in potato leaves increases the development and survival of serpentine leaf miner, *L. trifolii* (Facknath and Lalljee 2005).

Crop rotation/intercropping

Crop rotation is another means of reducing insect infestation. It breaks the continuity of the food chain of oligophagous pests. A carefully selected cropping system (intercropping or mixed cropping) can be used to reduce pest incidence, and/or, minimize the risks involved in monocultures. Sorghum is generally rotated with cotton, groundnut, sunflower, or sugarcane to reduce the damage by *A. soccata*, *S. sorghicola*, and *Calocoris angustatus* (Leth.) (Sharma 1985). Intercropping sorghum with pigeonpea reduces the damage by *H. armigera* in pigeonpea (Hegde and Lingappa 1996). Carrot intercropped with lucerne has been shown to suffer less damage by the carrot fly, *Psila rosae* F. (Ramert 1993), while intercropping red clover with maize reduces the damage by the European corn borer, *Ostrinia nubilalis* (Hubner) (Lambert et al. 1987).

Agronomic practices

Collecting and burning of stubbles and chaffy panicles reduces the carryover of spotted stem borer, *C. partellus* and midge, *S. sorghicola* in sorghum (Gahukar and Jotwani 1980; Sharma 1985). Piling and burning of trash at dusk in the field attracts the adults of white grubs, *Holotrichia consanguinea* (Blanchard) and the red hairy caterpillar, *Amsacta moorei* Buttler, and kills them. Ploughing the fields after crop harvest and before planting reduces the abundance and carryover of white grubs, grasshoppers, hairy caterpillars, noctuids, and pyralids by exposing them to parasites, predators, and adverse weather conditions (Gahukar and Jotwani 1980). Timely weeding also reduces the damage by some insect species (Sharma et al. 2004).

Chemical control

Insecticides are one of the most powerful tools in pest management. Insecticides are highly effective, rapid in action, adaptable to most situations, flexible enough to meet the changing agronomic requirements, and economical. When used properly based on economic thresholds, insecticides provide a dependable tool to protect the crops from insect pests. Despite their effectiveness, much of the insecticide use has been unsound, leading to problems such as pest resurgence, development of resistance, pesticide residues, nontarget effects, and direct hazards to the human beings (Smith et al. 1974). Insecticide use often results in direct and indirect toxicity to the natural enemies.

However, control measures directed at adults, eggs, and neonate larvae are most effective in minimizing insect damage. Spray decisions based on egg counts could destroy both invading adults and eggs, and leave a residue to kill future eggs and the neonate larvae. Young larvae are difficult to find, and at times burrow into the plant parts where they become less accessible to contact insecticides, and therefore, difficult to use as a criteria to determine economic thresholds. The agrochemical industry in India produces nearly 47,020 metric tons of pesticides (Krishna et al. 2006) (Fig. 3). Although pesticide consumption in India is quite low (around 500 g ha^{-1}) as compared to other countries such as Japan (12 kg ha^{-1}) and Germany (3 kg ha^{-1}), however, the problems resulting from indiscriminate use of pesticides are quite alarming.

The efficacy of insecticides against the insect pests also depends on the formulation, type of application, and the technology for delivering the insecticides. Some of the application equipment does not give the desired performance for specific crop-pest, climatic, and topographic conditions. There is a need to devise suitable application equipment to meet the farmers' needs in rainfed agriculture. Further, the types of insecticide formulations needed in rainfed areas are different from those for irrigated areas. Dry areas need different types of pesticide formulations, which require minimum amount of water. Hence, research efforts should be focused on developing right type of plant protection equipment and insecticide formulations to increase the efficiency of chemical control.

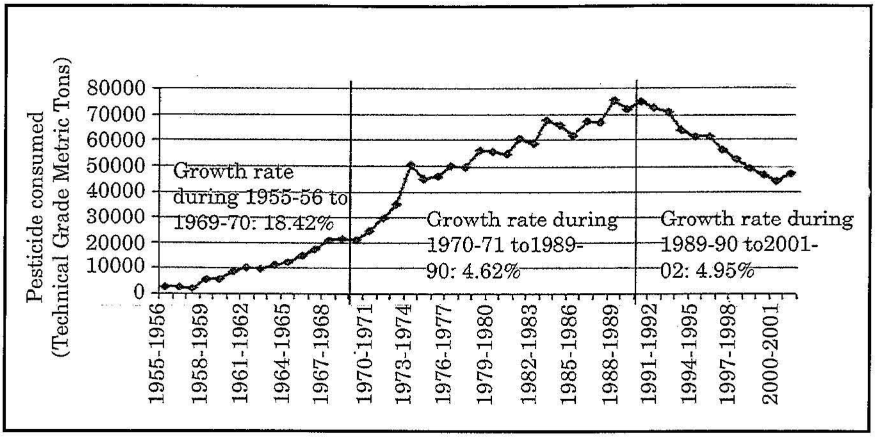


Fig. 3: Consumption of pesticides in India (Krishna et al. 2006).

Pesticides of plant origin

A large number of plant products derived from neem, custard apple, tobacco, pyrethrum, etc. have been used as safer pesticides for pest management. Neem derivatives comprise a complex array of novel compounds with profound behavioral and physiological effects such as repellence, phagodeterrance, growth disruption, and inhibition of oviposition (Schmutterer and Ascher 1984). Some of these effects have been attributed to azadirachtin, salannin, nimbin, zedunin, and meliantriol (Sharma et al. 1984, 1999). The complexity of the chemical structures of neem compounds precludes their synthesis on a practical scale. Therefore, use of neem leaf and seed kernel extract, and neem oil has been recommended for pest management. While neem is active against a wide range of insect pests, it is known to have little or no effect against major groups of beneficial insects such as spiders, ladybird beetles, parasitic wasps, and predatory mites (Schmutterer and Ascher 1984). Identification and promotion of pesticides of plant origin is one of the alternatives to overcome the ill effects of pesticides. At present, neem products are being marketed globally, although their production and use is limited by the availability of quality raw material. Efforts are needed to identify more molecules of plant origin so that they can be synthesized and used successfully in pest management in future.

Host plant resistance

Host plant resistance (HPR) along with natural enemies and cultural practices can play a major role in pest management (Painter 1951; Smith 1989; Sharma and Ortiz 2002; Sharma 2009). In spite of the importance of HPR as an important component of IPM, breeding for plant resistance to insects has not been as rapidly accepted as has been the case in breeding disease-resistant cultivars. This was partly due to the relative ease with which insect control is achieved with the use of insecticides, and the slow progress in developing insect-resistant cultivars. High levels of plant resistance are available against a few insect species only. However, very high levels of resistance are not a pre-requisite for use of HPR in IPM. Varieties with low to moderate levels of resistance or those which can avoid the pest damage can be deployed for pest management in combination with other components of pest management (Panda and Khush 1995; Sharma 2009). Deployment of pest-resistant cultivars should be aimed at conservation of the natural enemies and minimizing the number of pesticide applications. Use of insect-resistant cultivars also improves the efficiency of other pest management practices, including the synthetic insecticides (Sharma 1993).

Host-plant resistance can be used as: i) a principal component of pest control, ii) an adjunct to cultural, biological, and chemical control, and iii) as a check against the release of insect susceptible cultivars. Several insect pests have been kept under check through the use of insect-resistant cultivars, *e.g.* grapevine phylloxera, *Phylloxera vitifoliae* (Fitch.) (resistant rootstocks from the United States); cotton jassid, *A. biguttula biguttula* (Krishna, Mahalaxmi, Khandwa 2, and MCU 5); wooly apple aphid, *Eriosoma lanigerum* (Hausmann) (Northern Spy rootstocks); Hessian fly, *Mayetiola destructor* (Say) (Pawnee, Poso 42, and Benhur); rice gall midge, *O. oryzae* (IR 36, Kakatiya, Surekha, and Rajendradhan), spotted alfalfa aphid, *Therioaphis maculata* (Buckton) (Lahontan, Sonora, and Sirsa); sorghum shoot fly, *A. soccata* (Maldandi, Swati, and Phule Yashoda); sorghum midge, *S. sorghicola* (ICSV 745, ICSV 88032, and ICSV 804); and sorghum head bug, *Eurystylus oldi* Poppius (*guinea* sorghums in West Africa) (Painter 1951; Adkisson and Dyck 1980; Maxwell and Jennings 1980; Sharma 2009).

Genetic engineering of crop plants and bio-control agents for pest management

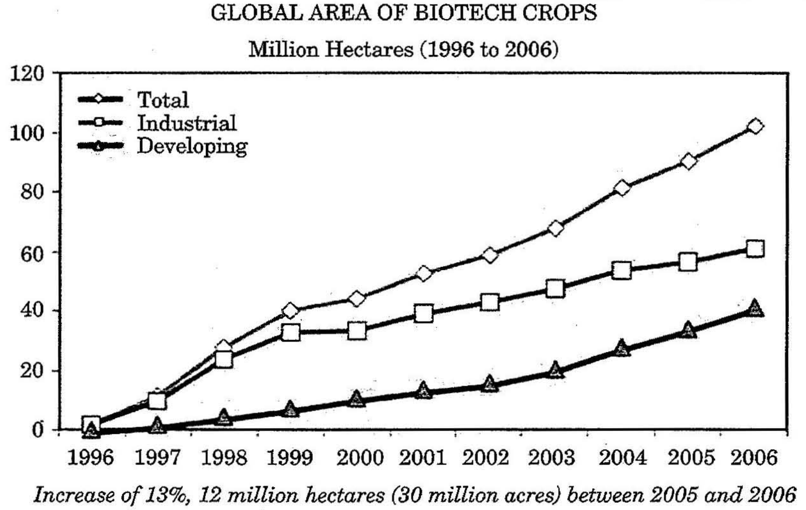
The promise of biotechnology as an instrument of development lies in its capacity to improve the quantity and quality of plants and biocontrol agents quickly and effectively. Genetic engineering reduces the time required to combine favorable traits over the conventional methods (Sharma 2009). Significant progress has been made over the past three decades in handling and introduction of exotic genes into crop plants. Genes from the bacteria such as *B. thuringiensis* have been used successfully for pest control through transgenic crops on a commercial scale. Trypsin inhibitors, lectins, ribosome inactivating proteins, secondary plant metabolites, vegetative insecticidal proteins, and small RNA viruses can be used alone or in combination with *Bt* genes (Hilder and Boulter 1999; Sharma et al. 2004). In addition to widening the pool of useful genes, genetic engineering also allows the introduction of several desirable genes in a single event, and thus, reduces the time required to introgress novel genes into the elite background.

Toxin genes from *Bt* have been inserted into the crop plants since mid 1980's. Since the first commercial deployment of transgenic crops in 1996, there has been a rapid growth in the area under transgenic crops in USA, Australia, China, India, etc. The area planted to transgenic crops increased from 1.7 million ha in 1996 to 148 million ha in 2010 (Fig. 4) (James 2007). In addition to the reduction in losses due to insect pests, the development and deployment of transgenic plants with insecticidal genes will also lead to:

- A major reduction in insecticide sprays.
- Increased activity of natural enemies.
- Reduced amounts of pesticide residues in the food and food products.
- Reduced exposure of farm labor and nontarget organisms to pesticides.

In addition, molecular approaches can also be used for:

- Diagnosis of insect pest and their natural enemies.
- Improve the natural enemies for resistance to insecticides and adaptation to adverse environmental conditions.



Increase of 13%, 12 million hectares (30 million acres) between 2005 and 2006

Source: Clive James, 12006

Fig. 4: Area under transgenic crops (1996–2006) (James 2007).

- Improve the virulence and persistence of biopesticides.
- Marker assisted selection to develop insect-resistant cultivars.
- Monitoring insect resistance to insecticides and development of new pesticide molecules.
- Understand plant-herbivore and insect host-natural enemy interactions.
- Functional genomics and metabolomics of plants and insects, and their interactions.

Biotechnology can help to achieve the productivity gains needed to feed the growing human population. Insect-resistant varieties and biocontrol agents will reduce the over dependence on pesticides, and thus, reduce the farmers' crop protection costs, benefiting both the environment and public health. Biotechnology would also offer cost-effective solutions to micronutrient malnutrition such as vitamin A, essential amino acids, and iron. Research in biotechnology on increasing the efficiency of utilising the farm inputs could also lead to development of crops that use water more efficiently and extract nutrients from the soil more effectively. The development of cereal plants capable of capturing nitrogen from the air could contribute greatly to plant nutrition, helping the poor farmers, who often cannot afford the use of costly fertilizers. However, there is a need to use the biotechnological interventions based on biosafety to the nontarget organisms, human beings, and the environment.

Integrated Pest Management: Theory and Practice

As a result of our quest for alternative methods of pest management, IPM has received far more attention than any other method of insect control. The term integrated control was first used by Bartlett (1956) and further elaborated by Stern et al. (1959) for integrating biological control with other methods of pest control, and later broadened to include a full array of pest management practices (Flint and van den Bosch 1981). The term IPM encompasses a comprehensive long-term pest management strategy based on ecosystem approach that takes into account economic, environmental, and social consequences of pest control interventions. In practice, IPM is based on periodical monitoring of pest populations, and using therapeutic or biological interventions as appropriate, based on economic thresholds.

IPM programs in practice have operated with the objective of managing the pesticides rather than managing the insect pests, but have certainly led to a considerable reduction in pesticide use. Various IPM programs have been developed in which different control tactics are integrated to suppress insect pest populations below the economic threshold (FAO 1995). These vary from judicious use of insecticides based on ETLs and regular scouting to sophisticated systems using computerized crop and population models to assess the need, timing, and selection of insecticides for pest management.

Classical integrated management programs for apple pests in Canada (Pickett and Patterson 1953) and for cotton pests in Peru (Dout and Smith 1971) provided some of the early models for successful implementation of IPM in the field (Norton et al. 2005). The Food and Agriculture Organization (FAO) subsequently provided the coordination to spread the IPM concept in developing countries. The success of IPM program in rice in South East Asia (FAO 1995) was based on linking outbreaks of the brown plant hopper, *N. lugens* with application of broad-spectrum insecticides, and the realization of the fact that the brown plant hopper populations were kept under check by the natural enemies in the absence of insecticide application. Much of the impact of this program was brought out through field demonstrations, training programs, and farmers' field schools. The success of some of these programs has led to the creation of Global IPM facility under the auspices of FAO, United Nations Development Program (UNDP), and World Bank, which will serve as a coordinating and promoting entity for IPM worldwide. The establishment of International Agricultural Research Centers (IARCs) has also contributed significantly to IPM, particularly through the development and promotion of pest-resistant cultivars worldwide. For sustainable IPM programs, we must aim at:

- Pest surveillance and forecasting.
- Need-based application of pesticides.
- Development and use of insect-resistant cultivars.
- Conservation and encouragement of natural enemies.
- Improved ecosystem management that minimizes insect damage.
- Utilization of natural plant products and biopesticides.
- Use molecular approaches for developing insect-resistant cultivars.

As a result of these efforts, there has been some reduction in pest outbreaks as well as pesticide use. In India, an area of 523,000 ha has been covered under IPM of various insect pests through augmentation and conservation of natural enemies (http://agricoop.nic.in/plantprotec02.htm). During the eight-year period from 1994-95 to 2001-02, the government of India spent nearly Rs.14,926 million for biocontrol of insect pests on different crops, covering a land area of 4.3 million ha.

Pest surveillance and fore-warning systems

Monitoring the density and movement of insect pests provides an early warning of pest invasion in an area or crop. Light and pheromone-baited traps have been used for monitoring insect populations (Nesbitt et al. 1979), but the relationship between eggs, larvae, and insect catch in traps is closest only when insect densities are low at the beginning of the season. It is important to record pest incidence through systematic surveys based on visual or sweep net counts. Insect population prediction models are useful for developing appropriate pest management strategies such as optimal timing of insecticide application (Apel et al. 1999), *e.g.*, SIRATAC - a computer-based pest management system has been developed to rationalize insecticide use on cotton (Hearn et al. 1981). This system incorporates a temperature driven cotton development model, including the natural fruiting habit of the plant, and sub-models to incorporate damage relationships, the impact of natural enemies, and predetermined or dynamic thresholds for insect pests. Several models have been developed for pest forecasting in different insect species and crops.

Mating disruption and mass trapping

Mating disruption using sex pheromones has been tried for controlling several insect pests such as pink bollworm, *P. gossypiella*; gypsy moth, *Lymantria dispar* L.; and codling moth, *Cydia pomonella* (L.) (Carde and Minks 1995). For insects such as cotton bollworm, *H. armigera*, which is a highly mobile pest, it is very difficult to control this pest through mating disruption unless thousands of hectares are treated simultaneously. For mating disruption, the pest should ideally be restricted to a single crop, otherwise all the target crops within an area need to be treated. The pheromone must be stable and formulated such that it releases the pheromone in a controlled manner in the crop habitat. Sex pheromones can also be used for mass trapping of some insects. It is necessary to catch 95% of the male moths to have any significant impact on the ability of the population to reproduce. Mobile insects such as *H. armigera* cannot be successfully controlled by mass trapping or mating disruption, as the females that have mated outside the treated area lay eggs in the area where the males may have been successfully removed. Mass trapping has been shown to work successfully for lepidopteran moths, which are relatively immobile such as rice stem borers; potato tuber moth, *Phthorimaea operculella* (Zeller); diamond back moth, *P. xylostella*; and brinjal fruit and shoot borer, *Leucinodes orbonalis* (Guen.) (Howse et al. 1997). For pests such as these, trap densities of 10 to 20 traps per ha. have been shown to be effective in reducing the damage levels.

Ecosystem management

The future IPM programs should be based on an understanding of the interactive food-webs in the ecosystem, and seek long-term benefits at the ecosystem level by harnessing the strengths of the ecosystem through ecosystem management. These should include:

- Crop attributes that discourage the pests, but encourage the effectiveness of the natural enemies.
- Measures that conserve the natural enemies, and increase their effectiveness for pest control.
- Use of therapeutics that cause minimal disruption in the ecosystem.

This would involve year round management of soil, weeds, cropping systems, water, fertilizer, and pesticide use at the community level, taking into consideration the effects of these practices on flora and fauna, and the ecological balance. Cover or intercrops, and relay or strip crops have been found to act as a bridge, and stabilize the balance between the natural enemies and the herbivores (Altieri 1994).

Multitrophic interactions

Crop plants are an important component of the multitrophic interactions. Plant traits have considerable impact both on the herbivores and their natural enemies. Plants have several morphological and biochemical traits that discourage the feeding by the herbivores. However, morphological and biochemical attributes of the plants also play an important role in influencing the ability of natural enemies to protect the plants against insect pests (Tumlinson et al. 1993). Some plants respond to herbivory by releasing chemical cues that attract the parasitoids and predators, which in turn, attack the herbivores (Dicke and Sabelis 1988; Dicke et al. 1990; Turlings et al. 1990). These chemicals are released only in response to insect feeding, but not due to mechanical injury, which enables the natural enemies to distinguish infested plants from the un-infested ones. By understanding the attributes of the defence mechanisms, these can be incorporated into the commercial cultivars to increase the effectiveness of natural enemies, while breeding crops for increased productivity or quality traits.

Need based application of selective pesticides

Need based application of pesticides will continue to play an important role in pest management, but they should be viewed as back ups rather than as a primary line of defense. They should be used to maintain the insect density within the economic threshold levels with minimal disruption to the environment. Semiochemicals, sex pheromones, and natural enemy attractants can be used to disrupt insect pests and encourage the activity of natural enemies. Entomopathogens and natural enemies can also be used as therapeutic interventions when the pest populations exceed threshold levels. There is a need to have greater focus, and provide additional incentives for production and use of biopesticides and natural enemies for pest management.

There is a need to use pesticides that are selective in nature, and are relatively safer to the natural enemies (Pfeiffer 1999). Some insecticides with broad-spectrum activity have been permitted for restricted use in agriculture, locust control, and public health programs. There is a growing concern to replace these pesticides with safer formulations or with pesticides of plant origin. Selective insecticides are products which primarily target the pest(s) you wish to control, with a few or no detrimental effects on pollinators and natural enemies. They may also have other attributes making them less harmful to the user and the environment, and may be grouped as biorational pesticides. Selective insecticides usually spare biological control agents, reduce the risk of secondary pest outbreaks, reduce the impact on the environment, improve farm safety, and minimize the number of pesticide applications needed. Broad-spectrum insecticides usually kill many insect species and beneficial organisms. Proper pesticide application and resistance management techniques should be used to maximize the effectiveness and preserve the useful life of the available products.

Use of appropriate pesticide formulations and application equipment

The efficacy of applied pesticides against the target pests depends upon the type of application equipment and technology of delivering the pesticide. Some of the application equipment does not give the desired performance in a specific crop - pest situation, and climatic and topographic conditions. There is a need to devise suitable application equipment for meeting the requirement of farmers in dry areas under rainfed conditions, and in hilly areas. Further, the types of pesticide formulations needed in rainfed areas are different from those for irrigated areas. Hence, research efforts should be concentrated for developing right type of plant protection equipment and pesticide formulations. Research efforts are also needed on mode of application that is least disruptive to the environment, *e.g.* seed treatment and granular application *vis-a-vis* sprays and dusts.

CONCLUSIONS

There has been a qualitative and quantitative change in pest spectrum and the pest control interventions over the past five decades. There would be immense benefits of systems approach to pest management, taking into account natural resources, biodiversity, landscape, and environmental conservation. We must develop farming practices that are compatible with the ecological systems, and avoid using crops, cultivars, and agronomic practices that help in elevation of an insect species to the level of a pest. Insect-resistant cultivars derived through conventional plant breeding or biotechnological approaches will continue to play a pivotal role in IPM in different crops and cropping systems. Efforts should be made to increase the activity and abundance of natural enemies through reducing pesticide application, and adopting cultivars/cropping practices that encourage their activity. Insecticide applications, in general, are more effective than the natural plant products, *Bt*, NPV, or the release of natural enemies. However, biopesticides applied in rotation or in combination with the synthetic insecticides can play an important role in IPM. There is a need to use modern tools of molecular biology to make pest management more effective, economic, and environment friendly for sustainable crop production.

References

Adkisson PL, Dyck VA. 1980. Resistant varieties in pest management systems. In: *Breeding Plants Resistant to Insects* (Maxwell FG, Jennings PR, eds.). John Wiley and Sons, New York, USA. pp. 233–251.

Altieri MA. 1994. *Biodiversity and Pest Management in Agro-ecosystems.* Haworth Press, New York, USA. 236 pp.

Altieri MA, Wilson RC, Schmidt LL. 1985. The effect of living mulches and weed cover on the dynamics of foliage and soil arthropod communities in three crop systems. *Crop Protection* 4: 2010–2013.

Anderson PK, Morales FJ. 2005. *White Fly and White Fly-borne Viruses in the Tropics: Building a Knowledge Base for Global Action.* International Center for Tropical Agriculture, Cali, Columbia. 351 pp.

Andow W. 1991. Vegetational diversity and arthropod population response. *Annual Review of Entomology* 36: 561–586.

Apel H, Herrmann A, Richter O. 1999. A decision support system for integrated pest management of *Helicoverpa armigera* in the tropics and subtropics by means of a rule-based Fuzzy-Model. *Zeitschrift fur Agrarinformatik* 7: 83–90.

Bartlett BR. 1956. Natural predators: Can selective insecticides help to preserve biotic control? *Agriculture Chemistry* 11: 42–44.

Bateman R, Carey M, Moore D, Prior C. 1993. The enhanced infectivity of *Metarrhizium flavoviride* in oil formulations to desert locusts at low humidities. *Annals of Applied Biology* 122: 145–152.

Bergman JM, Tingey WM. 1979. Aspects of interaction between plant genotypes and biological control. *Bulletin of Entomological Society of America* 25: 275–279.

Bugg RL, Ehler LE, Wilson LT. 1987. Effect of common knotweed (*Polygonum viculare*) on abundance and efficiency of insect predators of crop pests. *Hilgardia* 55: 1–53.

Carde RT, Minks AK. 1995. Control of moth pests by mating disruption – successes and constraints. *Annual Review of Entomology* 40: 559–585.

Chand P, Sinha MP, Kumar A. 1979. Nitrogen fertilizer reduces shoot fly incidence in sorghum. *Science and Culture* 45: 61–62.

Corbett A, Plant RE. 1993. Role of movement in the response of natural enemies to agroecosystem diversification: a theoretical evaluation: *Environmental Entomology* 22: 519–531.

Dicke M, Sabelis MW. 1988. How plants obtain predatory mites as bodyguards? *Netherlands Journal of Zoology* 38: 148–165.

Dicke M, Sabelis MW, Takabayashi J, Bruin J, Posthumus A. 1990. Plant strategies of manipulating predator-prey interactions through allelochemicals: prospects for application in pest control. *Journal of Chemical Ecology* 16: 3091–3118.

Dout RL, Smith RF. 1971. The pesticide syndrome – diagnosis and prophylaxis. In: *Biological Control* (Huffaker CB, ed.). Plenum Press, New York, USA. pp. 3–15.

Dulmage HD. 1970. Insecticidal activity of HD-1, a new isolate of *Bacillus thuringiensis* var. *alesti*. *Journal of Invertebrate Pathology* 15: 232–239.

Facknath S, Lalljee B. 2005. Effect of soil-applied complex fertilizer on an insect–host plant relationship: *Liriomyza trifolii* on *Solanum tuberosum*. *Entomologia Experimentalis et Applicata* 115: 67–77.

Flint ML, von den Bosch R. 1981. *Introduction to Integrated Pest Management.* Plenum Press, New York, USA. 240 pp.

Food and Agriculture Organization (FAO). 1995. *Inter-country Program for the Development and Application of Integrated Pest Control in Rice in South and South-East Asia.* Food and Agriculture Organization Plant Protection Service, Rome, Italy. 9 pp.

Fuxa JR. 2004. Ecology of insect nucleopolyhedrosis viruses. *Agriculture, Ecosystems & Environment* 103: 27–43.

Gahukar RT, Jotwani MG. 1980. Present status of field pests of sorghum and millets in India. *Tropical Pest Management* 26: 138–151.
Georgis R. 1992. Present and future prospects for entomopathogenic nematode products. *Biocontrol Science and Technology* 2: 83–99.
Hajeck AE, St-Leger RJ. 1994. Interactions between fungal pathogens and insect hosts. *Annual Review of Entomology* 39: 293–322.
Hearn AB, Ives PM, Room PM, Thomson NJ, Wilson LT. 1981. Computer-based cotton pest management in Australia. *Field Crops Research* 4: 321–332.
Hegde R, Lingappa S. 1996. Effect of intercropping on incidence and damage by *Helicoverpa armigera* in pigeonpea. *Karnataka Journal of Agricultural Sciences* 9: 616–621.
Hilder VA, Boulter D. 1999. Genetic engineering of crop plants for insect resistance - a critical review. *Crop Protection* 18: 177–191.
Howse P, Stevens JM, Jones O. 1997. *Insect Pheromones and Their Use in Pest Management*. Marcel Dekker Inc., New York, USA. 384 pp.
James C. 2007. *Global Status of Commercialized Biotech / GM Crops: 2006*. ISAAA Briefs no. 35. International Service for Acquisition of Agri-Biotech Applications (ISAAA), Ithaca, New York, USA. http://www.isaaa.org/resources/publications/briefs/35.
King EG, Coleman RJ. 1989. Potential for biological control of *Heliothis* species. *Annual Review of Entomology* 34: 53–75.
Kranthi KR, Jadhav DR, Kranthi S, Wanjari RR, Ali SS, Russel DA. 2002. Insecticide resistance in five major insect pests of cotton in India. *Crop Protection* 21: 449–460.
Krishna VV, Vyju NG, Tamizheniyan S. 2006. Integrated pest management in Indian agriculture: A developing economy perspective. In: *Radcliffe's IPM Text Book*. University of Minnesota, USA (http://ipmworld.umn.edu/ipmchap.htm). (last modified 26 may 2006).
Lambert B, Peferoen M. 1992. Insecticidal promise of *Bacillus thuringiensis*. *Bioscience* 42: 112–121.
Lambert JDH, Arnason JT, Serratos A, Philogene BJR, Faris MA. 1987. Role of intercropped red clover in inhibiting European corn borer (Lepidoptera: Pyralidae) damage to corn in eastern Ontario. *Journal of Economic Entomology* 80: 1192–1196.
Lewis WJ, van Lantern JC, Pathak SC, Tumlinson III JH. 1997. A total system approach to sustainable pest management. *Proceedings, National Academy of Sciences, USA* 94: 12243–12248.
Maxwell FG, Jennings PR (eds.). 1980. *Breeding Plants Resistant to Insects*. John Wiley and Sons, New York, USA. 683 pp.
Moscardi F. 1999. Assessment of the application of baculoviruses for control of Lepidoptera. *Annual Review of Entomology* 44: 257–289.
Myers N. 1999. The next green revolution: its environmental underpinnings. *Current Science* 76: 507–513.
Navon A. 2000. *Bacillus thuringiensis* insecticides in crop protection. – reality and prospects. *Crop Protection* 19: 669–676.
Neale MC. 1997. Bio-pesticides – harmonization of registration requirements within EU directive 91–414. An industry view. *Bulletin OEPP* 27: 89–93.
Nesbitt BF, Beevor PS, Hall DR, Lester R. 1979. Female sex pheromone components of the cotton bollworm *Heliothis armigera*. *Journal of Insect Physiology* 25: 535–541.
Norton GW, Heinrichs EA, Luther GC, Irwin ME (eds.). 2005. *Globalizing Integrated Pest Management: A Participatory Research Process*. Blackwell Publishing, Oxford, London, UK. 338 pp.
Oerke EC. 2006. Crop losses to pests. *Journal of Agricultural Science* 144: 31–43.
Painter RH. 1951. *Insect Resistance in Crop Plants*. MacMillan, New York, USA. 520 pp.
Panda N, Khush GS. 1995. *Host Plant Resistance to Insects*. CAB International, Wallingford, Oxon, UK. 431 pp.

Pawar CS, Bhatnagar VS, Jadhav DR. 1986. *Heliothis* species and their natural enemies, with their potential for biological control. *Proceedings of the Indian Academy of Science (Animal Science)* 95: 695–703.

Pfeiffer DG. 1999. Selective insecticides. In: *Insect Pest Management* (Rechcigl NA, ed.). CRC Press, Bota Racon, USA. pp. 131–144.

Pickett AD, Patterson NA. 1953. The influence of spray programs on the fauna of apple orchards in Novo Scotia. IV. A review. *Canadian Entomologist* 85: 472–478.

Pinstrup-Andersen P, Cohen M. 2000. Modern biotechnology for food and agriculture: Risks and opportunities for the poor. In: *Agricultural Biotechnology and the Poor* (Persley GJ, Lantin MM, eds.). Consultative Group on International Agricultural Research, Washington DC, USA. pp. 159–172.

Poinar Jr GO. 1990. Taxonomy and biology of Steinernematidae and Heterorhabtidae. In: *Entomopathogenic Nematodes in Biological Control* (Gaugler R, Kaya HK, eds.). CRC Press, Boca Raton, Florida, USA. pp. 23–61.

Pokharkar DS, Chaudhary SD, Verma SK. 1999. Utilization of nuclear polyhedrosis virus in the integrated control of fruit-borer (*Helicoverpa armigera*) on tomato (*Lycopersicon esculentum*). *Indian Journal of Agricultural Sciences* 69: 185–188.

Ramert B. 1993. Mulching with grass and bark and intercropping with *Medicago littoralis* against carrot fly, *Psila rosae* (F.). *Biological Agriculture and Horticulture* 9: 125–135.

Saxena H, Ahmad R. 1997. Field evaluation of *Beauveria bassiana* (Balsamo) Vuillemin against *Helicoverpa armigera* (Hubner) infecting chickpea. *Journal of Biological Control* 11: 93–96.

Schmidt MH, Thewes H, Thies C, Tscharntke T. 2004. Aphid suppression by natural enemies in mulched cereals. *Entomologia Experimentalis et Applicata* 113: 87–93.

Schmutterer H, Ascher KRS (eds.). 1984. *Natural Pesticides from the Neem Tree and Other Tropical Plants.* German Society for Technical Cooperation (GTZ), Eschborn, Germany. 587 pp.

Schweissing FC, Wilde G. 1979. Temperature and plant nutrient effects on resistance of seedling sorghum to the greenbug. *Journal of Economic Entomology* 72: 20–23.

Sharma HC. 1985. Strategies for pest control in sorghum in India. *Tropical Pest Management* 31: 167–185.

Sharma HC. 1993. Host plant resistance to insects in sorghum and its role in integrated pest management. *Crop Protection* 12: 11–34.

Sharma HC (ed.). 2005. Heliothis/Helicoverpa *Management: Emerging Trends and Strategies for Future Research.* Oxford & IBH, and Science Publishers, USA, New Delhi, India. 469 pp.

Sharma HC. 2009. *Biotechnological Approaches for Pest Management and Ecological Sustainability*. CRC Press, New York, USA. 526 pp.

Sharma HC, Ortiz R. 2002. Host plant resistance to insects: An eco-friendly approach for pest management and environment conservation. *Journal of Environmental Biology* 23: 111–135.

Sharma HC, Leuschner K, Sankaram AVB, Gunasekhar D, Marthandamurthi K, Bhaskariah M, Subramanyam M, Sultana N. 1984. Insect antifeedants and growth inhibitors from *Azadirachta indica* and *Plumbago zeylanica*. In: *Natural Pesticides from the Neem Tree and Other Tropical Plants* (Schmutterer H, Ascher KRS, eds.). German Society for Technical Cooperation (GTZ), Eschborn, Germany. pp. 291–320.

Sharma HC, Pampapathy G, Sullivan DJ. 2003. Influence of host plant resistance on activity and abundance of natural enemies. In: *Biological Control of Insect Pests* (Ignacimuthu S, Jayaraj S, eds.), Phoenix Publishing House, New Delhi, India. pp. 282–296.

Sharma HC, Sankaram AVB, Nwanze KF. 1999. Utilization of natural pesticides derived from neem and custard apple in integrated pest management. In: *Azadirachta indica* A. Juss. (Singh RP, Saxena RC, eds.). Oxford & IBH Publishing Co., New Delhi, India. pp. 199–211.

Sharma HC, Sullivan DJ, Sharma MM, Shetty SVR. 2004. Influence of weeding regimes and pearl millet genotypes on parasitism of the Oriental armyworm, *Mythimna separata*. *BioControl* 49: 689–699.

Sharma HC, Veerbhadra Rao M (eds.). 1995. *Pests and Pest Management in India: The Changing Scenario*. Plant Protection Association of India, Rajendranagar, Andhra Pradesh, India. 312 pp.

Shelton AM, Wyman JA, Cushing NL, Apfelbeck K, Dennehy TJ. 1993. Insecticide resistance of diamondback moth (Lepidoptera: Plutellidae) in North America. *Journal of Economic Entomology* 86: 11–19.

Smith CM. 1989. *Plant Resistance to Insects*. John Wiley and Sons, New York, USA. 286 pp.

Smith RF, Huffaker CB, Adkisson PL, Newsom DL. 1974. Progress achieved in the implementation of integrated control projects in the USA and tropical countries. *EPPO Bulletin* 4: 221–239.

Stern VM, Smith RF, van den Bosch, Hagen KS. 1959. The integrated control concept. *Hilgardia* 29: 81–101.

Sunderland K, Samu K. 2000. Effects of agricultural diversification on the abundance, distribution, and pest control potential of spiders: a review. *Entomologia Experimentalis et Applicata* 95: 1–13.

Swaminathan MS. 2000. Genetic engineering and food security: Ecological and livelihood issues. In: *Agricultural Biotechnology and the Rural Poor* (Persley GJ, Lantin MM, eds.). Consultative Group on International Agricultural Research, Washington DC, USA. pp. 37–44.

Topham M, Beardsley Jr JW. 1975. Influence of nectar source plants on the New Guinea sugarcane weevil parasite, *Lixophaga sphenophori* (Villeneuve) *Proceedings, Hawaiian Entomology Society* 22: 145–154.

Tumlinson JH, Lewis WJ, Vet LEM. 1993. Parasitic wasps, chemically guided intelligent foragers. *Scientific American* 268: 100–106.

Turlings TCJ, Tumlinson J, Lewis WJ. 1990. Exploitation of herbivore-induced plant odors by host-seeking parasitic wasps. *Science* 250: 1251–1253.