Chapter 6
Advances in Crop Protection Practices for the Environmental Sustainability of Cropping Systems

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Abstract The era of green revolution has witnessed a tremendous change in the outlook of agriculture development. Green revolution emphasized the increased availability of food grains through the use of high yielding varieties, plant protection measures, and application of increased dosage of synthetic fertilizers, coupled with irrigation management. It not only increased the food grain production but also the utilization of synthetic fertilizers and pesticides. Over-reliance on the use of pesticides during green revolution has resulted in environmental pollution, ground water contamination, resurgence of pests, and poisoning of food sources, animals and human beings. Extensive application of fertilizers has changed the soil properties and acts as a major barrier in sustainable agriculture production. Farmers and agro-based industries could thrive only through the technological innovation that goes in harmony with IPM practices. Several advances have been made in the research and implementation of control strategies for the management of pests and diseases, which could be integrated into a sustainable agricultural system. The chapter focuses on these advances in various control measures and gives an account of various successful IPM programs from around the world. The success of any IPM program would depend on the understanding and acceptance from the farmers, and the integrated approach needed in form of policy making, communication and networking from the governmental and non-governmental agencies. The policy makers have to be advised to allocate budget for the extensive training, motivation of farmers and promotion of IPM through the establishment of IPM networks. Restructuring, both research and policy issues, will pave way for sustainable agriculture production through IPM.

Keywords Biological control · Bacteria · Fungi · Plant diseases · Antibiotics · IPM

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6.1 Introduction

Agriculture development over years has witnessed a marvelous change after the inception of green revolution. Green revolution ensured the increased availability of food grains through the use of high yielding varieties, plant protection measures, application of increased dosage of synthetic fertilizers coupled with irrigation management. With the introduction of improved technologies, the food production has outstripped population growth in the last few decades and continues to grow. Besides the increased productivity, the improved technologies resulted in the increased consumption of synthetic fertilizers and pesticides. In developing countries like India, agricultural statistics emphasized that the consumption of pesticides before green revolution was around 2330 MT, however the same during green revolution in the 1960s increased to 75,000 MT (Raghunathan, 2005). Expenditure on pesticides in U.S. agriculture increased eight-fold from 1950 to 1999 to $8.8 billion (in year-2000 dollars). Pesticide expenditures rose from 1.6% to 7.5% of total purchased inputs. This increase was widespread across crops and regions (United States Department of Agriculture, Economic Research Service, 2001) much had become a mainstay in many countries. Over reliance on the use of pesticides has resulted in environmental pollution, ground water contamination, and development of resurgence in pests, and poisoning of food material, animals and human beings. In addition, it also affected the agricultural trade where several agricultural commodities were rejected due to the accumulation of pesticide residues.

The economic liberalization, globalization and the WTO policies have necessitated a paradigm shift in agriculture. To meet the stringent demands put forth by WTO, and the phytosanitary standards prescribed by the importing countries, the environment policy has to be restructured so as to minimize the extensive usage of pesticides. However, recent agricultural policies emphasize agriculture as an engine for growth by accelerating the development of commercial agriculture, agro-industry and agro-exports. The need for sustainability in agriculture, to satisfy changing human needs and enhancing the quality of the environment is being addressed by policy makers and scientists globally. To be sustainable the practices have to be ecologically sound, economically viable, socially justifiable and adaptable.

Introduction of sustainable farming practices, including integrated pest management (IPM), will create a paradigm shift in agriculture. "Integrated pest management is a pest management system that in the socio-economic context of farming systems, the associated environment and the population dynamics of the pest species, utilizes all suitable techniques in as compatible manner as possible and maintains the pest population levels below those causing economic injury" (Dent, 1995).

IPM being a knowledge-intensive and farmer based decision making process, encourages natural control of pests and diseases from reaching economically damaging levels. It prevents the outbreak of resurgence among the pests and development of resistance among the plant pathogens. The pesticide free agricultural commodities from the IPM practiced fields have a great scope to increase the income of farmers. In spite of several advantages, the levels of adoption of IPM by the farmers are very slow. Hence, there is a challenging task for the government, researchers and extension functionaries to identify the reasons for poor adoption and to design policies that motivate the farming community to adopt the IPM practices.

6.2 Management of Insects Pests and Diseases

Implementation of effective pest and disease management programs demands achievement of goals and allowing the system to evolve with experience. Although the future demands for quality food production and export requires residue free food products, the usage of pesticides and fungicides has to be appropriate, that it not only controls pest and diseases but at the same time ensures that the residue accumulation is under permissible limits as prescribed by the importing countries. These goals can be achieved by introducing IPM/IDM, which adheres to the following basic principles:

- The maximum use of production inputs that are internal to the system, i.e. incorporating indigenous knowledge on pest control, enhancing natural control process via vegetation management, and wise and judicious use of pesticides.
- The development or redevelopment of germplasm well adapted to local conditions and pest problems.
- The development of farmer-participatory process by researchers to stimulate the acquisition and use of technological information by farmers.

Maintaining crop habitat diversity, adoption of various cultural and behavioral methods, growing of resistant varieties, rationalization of pesticides use and integration of biopesticides have been demonstrated in management of pests and are attractive tools in IPM in view of their ecofriendly nature (Jayaraj et al., 1994).

6.2.1 Habitat Diversification

The cropping system approach in IPM is a low input system, which existed in subsistence farming. This traditional method of farming practice needs a modern touch in view of plant-host-natural enemy relationship. The existing habitat structure should be designed considering the complex system of the biodiversity of the host plants, pests/ pathogens/ weeds, their natural enemies and their interaction.

Sustainable systems of agricultural production are seen in areas where proper mixes of crops and varieties are adopted in a given agroecosystem. Monocultures and overlapping crop seasons are more prone to severe outbreak of pests and diseases. One of the reasons for adoption of mixed cropping in marginal farming and in rainfed ecosystem is due to the low incidence of pests and diseases (Jayaraj, 1987) which was due to the increased activity of natural enemies (Bhatnagar and Davies, 1980). The diversity of natural enemies that attack pests at various stages of the life cycle is greater in poly crop systems, which also tends to prevent severe pest outbreaks. The cropping system approach proliferates natural enemies by providing food and shelter and prevents the evacuation of these biological control agents from the agroecosystem by biological (host plant, prey density) and physical (protection from wind, hiding, shading) interference mechanisms.

6.2.2 Integration of Host Plant Resistance

Technical advancements in containing the crop pests have been successful in the area of host plant resistance. More than 500 cultivars resistant to crop pests of economic importance have been developed and grown in many countries and have proved to be ecologically and economically superior insect control tools in global agriculture for over 30 years (Chelliah and Uthamasamy, 1998). In the context of integration of resistant cultivars in crop protection, continuous cultivation of resistant varieties with a narrow genetic base for a long period might lead to development of biotypes. Strategies include sequential release of varieties with major genes, pyramiding of genes, use of multiline varieties, incorporation of polygenes and wide hybridization (Jayaraj, 1990). With the advent of genetic transformation techniques, it has become possible to insert exotic genes into the plant genome that confers resistance to insects. Genes from bacteria, trypsin inhibitor, lectins, ribosome inactivating proteins, secondary plant metabolites, vegetative insecticidal proteins and small RNA have been in use for resistance buildup in crops (Sharma and Ortiz, 2000). In India, at least 12 research organizations are involved in plant transformation work for developing novel plants with new genetic traits for resistance to insects (Ghosh, 1999). While host plant traits for resistance has so far been practiced as the principle method of pest management by farmers, they have added advantage in crop protection of being complementary to biological and insecticidal control (Uthamasamy, 1998) and botanical pest control (Abdul Kareem and Gunasekaran, 1998). Huang et al. (2003) reported that Bt cotton significantly reduces the number of sprayings, the quantity of pesticides used and the level of pesticide expenditures. They also state that such reductions in pesticides also likely lead to labour savings, more efficient overall production, as well as positive health and environmental impacts. Modern cropping practices need adjustments in growing resistant crop varieties under polycrop situations in which greater habitat diversification is possible. The main crops can be attractive to the natural enemies, while the pests are deterred away from causing economic damage. A two year field study in Manitoba, Canada, evaluated the effect of wheat cultivar mixtures on disease levels. It was found that wheat cultivar mixtures provided yield stability and resulted in lower disease levels than some varieties of monocropped wheat (Natural Systems Agriculture, 2007).

6.2.3 Biological Control of Pests

Biopesticides like pathogens, parasitoids, predators and antagonistic organisms have become invaluable components in agricultural IPM systems. In addition to the natural biocontrol operating in many crop habitats, applied biocontrol can bring about a successful suppression of crop pests, diseases and nematodes without disrupting the ecosystem, The high level of human safety, stability of control and renewable nature, make biopesticides very attractive candidates for pest management (Jayaraj et al., 1994). In recent times, biological control has expanded from the use of entomophagous insects to the use of a whole range of organisms to control insects and nematodes. Biological control has been used as an end in itself rather than as a synergistic component of integrated pest management. After nearly two decades of intensive teaching and field level training, farmers have understood the value of biological control. Some of the notable success achieved with entomophagous insects and microbials in India is presented. (Tables 6.1 and 6.2).

6.2.3.1 Bio-Control of Pests Worldwide

Biological control has been well adopted as a mean of pest control in many parts of the world. Biocontrol strategies which involve the use of parasitoids, predators and pathogenic microbes have been success stories in many countries. A brief summary of some case studies are presented.

Cotesia rubecula (Marshall) has demonstrated the reduction of population of *Pieris rapae* L., a European butterfly that infests garden cabbage and other cole crops. The parasitoid has been an important source of mortality of the pest in the USA. The study also found that population of one non-native butterfly was also reduced in the northeastern USA by another introduced parasitoid *C. glomerata* L. This proves that introduction of natural enemies often focus on the eradication of

Table 6.1 Potential entomophages in IPM systems

Pest	Parasitoids
Scirpophaga incertulas (Walker)	*Trichogramma chilonis* (Ishii),
Chilo infuscatellus (Snellen)	*T. japonicum* (Ashmead), *Tetrastichus schoenobii* (Ferr).
Chilo sacchariphagus indicus (Kapur)	*Epiricania melanoleuca* (Fletcher)
Pyrilla perpusilla (Walker)	*Adelencyrtus mayurai* (Subba Rao)
Earias vitella (Sherborn)	*Rhogas aligarhensis* (Qadri)
Plutella xylostella (Linnaeus)	*Apanteles plutellae* (Kurdjumov)
Opisina arenosella (Walker)	*Goniozus nephantidis* (Musebeck)
Pest	Predators
Grapevine, citrus and coffee mealy bugs	*Cryptolaemus montrouzieri* (Mulsant), *Chrysoperla carnea* (Stephens), *Cheilomenes sexmaculata* (Fabricius),
Aphids, whiteflies, young larvae of Lepidoptera on cotton	*Coccinella arcuata* (Fabricius), *Syrphus indicus* *Lycosa pseudoannulata* (Bosenberg and Strand),
Rice brown planthopper, Green leafhopper, White-backed planthopper.	*Cyrtorhinus lividipennis* (Reuter),

Table 6.2 Potential entomophages in IPM systems

Pest	Pathogens
Helicoverpa armigera (Hubner), *Spodoptera litura* (Fabricius), *Amsacta albistriga* (Walker), *Plutella xylostella* (Linnaeus), *Spilosoma oblique* (Walker), *Hyblaea puera* (Cramer)	Respective Nuclear Polyhedrosis Viruses (NPVs)
Chilo infuscatellus (Snellen) *Chilo sacchariphagus indicus* (Kapur) *H. armigera* (Hubner) *Oryctes rhinoceros* (Linnaues)	Respective Granulosis Viruses (GV)
Nilaparvata lugens (Stal)	Non-occlusion virus, *Metarhizium anisopliae* (Metsch).
H. armigera, P. xylostella, Cnaphalocrocis medinalis (Guenee)	*Beauveria bassiana* (Bals.), *Nomuraea rileyi* (Farlow) Samson, *Bacillus thuringiensis* (Berliner)

the pest, rather than on the bigger project of incorporating pre and post introduction evaluations on the target and related non-target organisms (Driesche, 2007). Biocontrol of *Mononychellus tanajoa* (Bondar), the cassava green mite, by *Typhlodromalus aripo* (DeLeon), a phytoseiid predator, in more than 20 countries of sub-Saharan Africa is a great example of classical biological control using introduced natural enemies (Yaninek, 2007). Biocontrol mediated by *Harmonia axyridis* (Pallas) (ladybird beetle), through predation, has been a success story in the USA: *Monellia caryella* (Fitch) (blackmargined aphid) and *Monelliopsis pecanis* (Bissell) (yellow pecan aphid) in pecan orchards in Georgia, USA (Tedders and Schaeffer, 1994); *Diaphorina citri* (Kuwayama) (Asian citrus psyllid) in citrus groves in Florida, USA (Michaud, 2004); *Macrosiphum euphorbiae* (Thomas) (potato aphid) in potato crops in northern Maine, USA (Alyokhin and Sewell, 2004). The decimation of *Lymantria dispar* L, the gypsy moth, the pest responsible for severe defoliation of decudious forests and shade trees in N. America, by *Entomophaga maimaiga* is a good example of the "enemy release hypothesis". This is so because high populations of this pest are not common in its areas of origin but severe outbreaks occur in North America where gypsy moth has invaded without its native natural enemies. The gypsy moth populations have remained at much lower levels after the introduction of the entomopathogenic fungus (Hajek, 2007). Biocontrol of the native New Zealand grass grub, *Costelytra zealandica* (White), by *Serratia entomophila* (Grimont) is also a success story. The bacteria cause Amber disease, which is caused by ingestion of pathogenic bacteria, rapidly causing cessation of feeding and gut clearance, which give the larvae their amber appearance (Jackson, 2007). In Brazil, an IPM project successfully implemented the use of a naturally occurring nucleopolyhedrovirus for the control of the velvetbean caterpillar, *Anticarsia gemmatalis* (Hubner), one of the most devastating pests of soybean. The virus is presently used in two million hectares of soybean production area in Brazil, representing the largest program worldwide for the use of an entomopathogen to control a pest in a single crop, which generated substantial economic, ecological and social benefits to Brazil (Moscardi, 2007). Biopesticide products based on the entomopathogenic nematodes and their symbionts are at present aimed almost exclusively at relatively small niche markets. Research outputs in the last decade points the potentiality of these organisms. Nematodes belonging to the groups viz., mermethids, neoaplectanids, sphaerulariids and entaphelenohids hold promise. Biological control of scarabaeid larvae, the pest of plantation trees and nursery plants, by entomopathogenic nematodes of the genera *Steinernema* and *Heterorhabdis* living in a close symbiotic association with bacteria of the genera *Xenorhabdus* and *Photorhabdus*. The dauern juveniles of the nematodes enter the insect host and release the symbiotic bacteria, which release toxins that kill the insect host. The bacteria proliferate in the insect cadaver, and are in turn fed on by the larvae, which develop to adults to produce off springs. The off springs develop into dauer juveniles which leave the insect cadaver in search of new hosts (Ehlers, 2007).

6.2.3.2 Efficacy of Biocontrol of Pests Under Field Conditions

Within the field of microbial control of agricultural pests, the use of entomopathogenic fungi has a special role, rather than nuclear polyhedrosis virus. They can develop independent of their host, which presents the opportunity for large-scale production of these fungi on liquid or solid media, which makes the use of entomopathogenic fungi as biocontrol agents technically and economically viable. Due to the ease of technical production, their host range, their capability of triggering epizootics, their temperature optimum and other ecological criteria, *Beauveria bassiana* (Bals.) Vuil. (Deuteromycotina: Hyphomycetes) and *Metarhizium anisopliae* (Metsch.) Sorok. (Deuteromycotina: Hyphomycetes) are the two species most frequently employed. The production of conidia on cereals has a long tradition in Latin America. In the 1970s, applications of *Metarhizium* covered an area of 100,000 ha/yr (Marques et al., 1981). In Cuba, 220 centers for the reproduction of entomophages and entomopathogens were created by the state. In 1994, 500 t of *B. bassiana* were applied to 400,000 ha of crops to control banana root weevil, *Cosmopolites sordidus* (Germ.) (Coleoptera: Curculionidae), citrus root weevil *Pachnaeus litus* (Germar) (Coleoptera: Curculionidae), and sweet potato weevil *Cylas furmicarius* Fabricius (Coleoptera: Apionidae).

Entomophthoralean fungi pathogenic to insects and mites cause and encourage spread of disease using different strategies. For example, insects infected by fungal pathogens may be induced to climb to the top of plants and firmly grip branches immediately before death, which enhances spread of the fungus in the field. Also, as the host sickens and dies, rhizoids sometimes grow through the insect's ventral surface to anchor the body firmly to the substrate. The conidiophores, in most species, forcibly discharge conidia. The entomophthoralean fungi *Batkoa* sp. and *Furia* sp. occur at epizootic levels in Brazil in spittlebug pests (Hemiptera: Cercopidae). *Neozygites oridana* has been found in many countries suppressing populations of some important mite pests in agriculture, including two-spotted spider mite, *Tetranychus urticae* (Koch.). *B. bassiana* is one of the most commonly occurring entomopathogenic fungal species, and shows strong pathogenicity to Lepidoptera, Hymenopterta, Coleoptera, and Leptinotarsa (Fernandez et al., 2001).

There have been some attempts to develop entomophthoraleans as practical biopesticides. The two most studied genera, *Zoophthora* and *Erynia*, have been produced through liquid fermentation, formulated as mycelium, and introduced into field conditions as an inoculating strategy. However, the research on the use of insect fungal pathogens for the management of pests in India is very limited, which requires an intensive search for the identification of fungal pathogens suited well for the tropical situations. Nevertheless, to develop as practical biopesticides, it is necessary to develop culture media and methods that not only maximize production, but also at an economical cost. This effort will entail in selecting the most favorable inexpensive components for pathogen growth, as well as the lowest concentrations that afford high yield.

6.2.4 Microbial Bio-Control of Plant Diseases

Steady increase in the global population demands a steady and healthy food supply. The demand for food production requires further intensification of agricultural practices, which in turn may increase the pressure on crop plants. To have a healthy cropping system to meet the demands of increased food production, yield losses resulting from plant diseases need to be curtailed. Practices involving improving the genetic resistance of the host plant, management of the plant and its environment, and use of synthetic pesticides play a key role in the control of plant diseases (Strange, 1993). Intensification of agricultural practices would result in increases in use of synthetic pesticides such as fungicides, which is of great concern. Use of synthetic chemicals is under extreme pressure due to their hazardous effects on the environment, and concern over non-target effects (Felton and Dahlman, 1984; Elmholt, 1991) and; development of resistance in pathogen populations (Ishii, 2006). Especially, the use of site – specific systemic fungicides has brought about numerous cases of fungicide resistance (Schumann, 1991). Also, there have been concerns over pesticide residues in food, which could lead to serious health concerns (Picó et al., 2006).

Biological control, which is a natural phenomenon, involving the use of microorganisms for disease control, seems to be a good alternative to chemical control. First and foremost, the highly diverse microbial community in the environment provides an endless source for this purpose (Emmert and Handelsman, 1999). Various studies have shown that increasing the population of a particular microbial strain in the vicinity of a host plant can control the disease without altering the rest of the microbial community or causing any adverse effects on other organisms in the ecosystem (Gilbert et al., 1993; Osburn et al., 1995; Ravnskov et al., 2002). In addition to this inundative approach, management and manipulation of natural communities of antagonistic microbes through crop rotation and organic amendments have proven to be highly effective forms of biological control (Hoitink and Boehm, 1999; Kurle et al., 2001; Coventry et al., 2005 (from Janvier et al., 2007)). It is also believed that the complexity in the interaction between the organisms in the ecosystem, the multiple mechanisms of disease suppression by a single microorganism, and the capability of the antagonist to adapt itself to the environment in which it is used, could make biological control a more durable system than synthetic chemicals (Cook, 1993; Benbrook et al., 1996; Weller, 2007).

6.2.4.1 Significance of Crop Growth Stage

The dynamics of PGPR, yeast, actinomycetes and pathogenic microbes are influenced by the exudates of roots in the rhizosphere region, which in turn alters the communication network and interaction between the beneficial, deleterious microflora and the plant system as a whole (Picard et al., 2000). Plant roots release a wide variety of compounds into the surrounding soil, including ethylene, sugars, amino acids, organic acids, vitamins, polysaccharides, and enzymes. These materials create unique environments for the microorganisms living in association with plant roots in the rhizosphere. Bacteria respond differently to the compounds released by the plant root, and thus different compositions of root exudates are expected to select different rhizosphere communities (Garbeva et al., 2004). On the other hand, rhizosphere bacteria will also influence plants, as wide ranges of bacteria in the rhizosphere can promote plant growth via chemical signals such as auxins, gibberellins, glycolipids, and cytokinins. Genera such as *Pseudomonas, Agrobacterium, Bacillus, Variovorax, Phyllobacterium*, and *Azospirillum* are among the most efficient plant growth – promoting bacteria (Bertrand et al., 2001). For example, *Azospirillum brasilense* (Tarrand) can exert a positive effect on the growth of common bean and soybean, and *Agrobacterium tumefaciens* (Smith and Townsend) can have a strong effect on plant root development (Burdman et al., 1997; Molla et al., 2001). The composition of root exudates is strongly affected by the plant developmental stage, which in turn can affect rhizosphere communities over time (Yang and Crowley, 2000). Picard et al. (2000) showed that the presence of 2,4-diacetylphloroglucinol (DAPG)-producing bacteria in the rhizosphere of maize was significantly affected by plant age. The frequency of DAPG producers was very low in the first stage of plant growth and increased over time. Plant age effects were also observed by di Cello et al. (1997) and Seldin et al. (1998), who showed that populations of *Burkholderia cepacia* ((Palleroni and Holmes) Yabuuchi) and *Peanibacillus azotofixans* in the maize rhizosphere changed during plant growth. Furthermore, Gyamfi et al. (2002) also confirmed that the plant growth stage had a strong impact on total bacterial as well as *Pseudomonas* communities. Yang and Crowley (2000) later confirmed these observations. The main sources of easily accessible substrates are sites at root tips and young roots. Thus, young plants provide the highest amount of organic carbon available for microbial growth. Young roots and root tips might therefore represent excellent niches suitable for colonization by r-strategists. Hence, understanding the distribution of genetic structure and the activity of a microbial community existing in the rhizosphere has a practical importance in the selection of a potential candidate for the management of plant diseases. This would facilitate to estimate the fate of released strains and their impact on both pests and disease causing organisms in the rhizosphere and phyllosphere due to the production of antibiotics (Picard et al., 2000).

6.2.4.2 Role of Antibiotic Producers

Direct antagonism of the pathogen through antibiosis is one of the mechanisms by which disease suppressive bacteria achieve disease control. Antibiosis is mediated through the production of a chemically heterogeneous group of organic, low-molecular mass compounds (Raaijmakers et al., 2002), which at low concentrations are deleterious to the growth or metabolic activities of other microorganisms (Fravel 1988; Thomashow et al., 1997).

Numerous studies on the role of antibiotics in biocontrol of plant pathogens have led to the isolation and characterization of numerous antibiotics from various bacterial genera. Some prominent examples are: control of *Gaeumannomyces graminis* var *tritici* (Walker) in wheat by phenazine produced by *Pseudomonas chlororaphis* PCL1391 (Chin-A-Woeng et al., 1998); control of multiple pathogens such as *Pythium aphanidermatum* ((Edson) Fitzpatrick), *Botryodiplodia theobromae* (Patouillard), and *Alternaria solani* ((Ellis et Martin) Sorauer) by phenazine produced by *P. chlororaphis* PA23 (Kavitha et al., 2005); control of *Rhizoctonia solani* (Kuhn) in cotton by pyrrolnitrin produced by *P. fluorescens* BL915 (Ligon et al., 2000); control of *Rhizoctonia solani* in poinsettia by pyrrolnitrin produced by *Burkholderia cepacia* (Hwang et al., 2002); control of *Thielaviopsis basicola* ((Berkeley et Broome) Ferraris) and *Pythium ultimum* (Trow) in cotton by pyoluteorin produced by *P. fluorescens* CHA0 (Maurhofer et al., 1992); control of *G. graminis* var *tritici* in wheat by 2–4, diacetylphloroglucinol produced by *P. fluorescens* Q8r1-96 (Raaijmakers and Weller, 2001); control of *Phytophthora medicaginis* in alfalfa by zwittermicin A produced by *B. cereus* UW85 (Silo-Suh et al., 1994); control of *Erwinia herbicola* (Lohnis) in apple by pantocin A and B produced by *P. agglomerans* EH318 (Wright et al., 2001); control of *P. ultimum* in sugar beets by xanthobaccins produced by *Stenotrophomonas* SB-K88 (Nakayama et al., 1999).

Pseudomonas chlororaphis strains PA23 (PA23) and DF190 are strong antagonists of *Sclerotinia sclerotiorum* de Bary and *Leptosphaeria maculans* (Desmazieres) Cesati et De Notaris, respectively. The bacteria were identified as producers of the antifungal antibiotics phenazine and pyrrolnitrin (Ramarathnam and Fernando, 2006; Zhang et al., 2006). The production of phenazines and pyrrolnitrin corresponds to the antifungal activity of PA23 culture extracts in the inhibition of sclerotial and/or spore germination of several plant pathogens. Production of multiple antibiotics, with overlapping or different degrees of activity, may account for the suppression of specific or multiple plant pathogens (Raaijmakers et al., 2002). Characterization of a PA23Tn5 mutant, called PA23-63, revealed a Tn insertion in *phzE*, which forms part of the phenazine biosynthetic cluster. Despite producing no phenazines, this strain exhibited wild-type levels of antifungal and biocontrol activity against *S. sclerotiorum* and *L. maculans* (Poritsanos, 2005; Ramarathnam, 2007). Our findings indicate that phenazine production is not essential for PA23 biocontrol of these two pathogens. MutantPA23-63 produces pyrrolnitrin at levels equal to that of the wild type (Paulitz, personal communication). Therefore, we believe that pyrrolnitrin is mainly, but not exclusively, responsible for the antibiosis-mediated biocontrol of *S. sclerotiorum*, the stem rot pathogen (Poritsanos, 2005), and *L. maculans*, the blackleg pathogen of canola (Ramarathnam, 2007). *Bacillus cereus* strain DFE4, and *B. amyloliquefaciens* strains BS6 and DFE16 exhibited agar-diffusible antifungal activity, and greenhouse and field suppression of sclerotina stem rot and blackleg of canola (Fernando, 2005; Ramarathnam, 2007). All three *Bacillus* strains harbour biosynthetic genes for the lipopeptide antibiotics iturin A, bacillomycin D and surfactin. Moreover, cell extract analysis by MALDI-TOF-MS (Matrix-Assisted Laser Desorption Ionization – Mass Spectrometry) confirmed the production of iturin A, bacillomycin D and surfactin by these biocontrol agents (Ramarathnam, 2007).

6.2.4.3 Role of Mycorrhizal Fungi

Arbuscular mycorrhizal (AM) fungi are ubiquitous soil microbes that form symbiotic associations with plant root systems. In forming such symbiotic associations, they colonize within and around the plant root system, forming internal structures that facilitate the transfer of photosynthetically derived carbon to the fungus. AM fungi are obligate symbionts and are dependent on this source of carbon for the completion of their life-cycle (Harrier and Watson, 2004). There is an apparent lack of host specificity with about 150 species of AM fungus demonstrating a wide host range for each individual species. This wide host range is deceptive, since there is a level of functional compatibility, shown by symbioses between different isolates of AM fungi and different plant species varying in compatibility. Therefore, selection of the isolate of AM fungus is critical for the optimisation of the benefits of the symbiosis *in situ*. It is now widely recognised that the soil conditions prevalent in sustainable agriculture are likely to be more favourable to AM fungi than those under conventional agriculture (Bethlenfalvay and Schüepp, 1994; Smith and Read, 1997). AM fungi have not been shown to interact directly with pathogens through antagonism, antibiosis and/or mycoparasitism. Cordier et al. (1996) and Davies and Menge (1980) demonstrated localised competition between AM fungi and *Phytophthora*, as *Phytophthora* development was reduced in AM fungal-colonised and adjacent un-colonized root system regions. Vigo et al. (2000) found that the number of infection sites was reduced within mycorrhizal root systems and that the colonisation by the AM fungus had no measurable effect on the spread of necrosis, thus suggesting that the number of infection sites was important for subsequent pathogen infection. The increase in lignification is thought to protect the roots from penetration by other pathogens, and results from an elevation of phenolic metabolism within the host plant (Morandi, 1996). Cordier et al. (1998) and Pozo et al. (2002) demonstrated that induced resistance against the pathogen *Phytophthora parasitica* (Dastur) in AM fungal-colonised tomato roots resulted from localised defence responses in arbuscule containing cells and systemic defence responses in non-mycorrhizal parts of mycorrhizal roots. The local induced resistance comprised the formation of cell wall appositions reinforced by callose adjacent to intercellular hyphae. The systemic resistance of non-mycorrhizal components of a mycorrhizal root system was characterised by the elicitation of host wall thickenings containing non-esterified pectins and PR-1a proteins in reaction to intercellular pathogen hyphae and by the formation of callose rich encasement material around *P parasitica* hyphae that were penetrating root cells. Therefore, the bioprotection conferred by AM fungal-colonisation of host plant root systems is both localised and systemic. De la Peña et al. (2006) reported that root infection and multiplication of *Pratylenchus penetrans* (Cobb) were significantly reduced by the native inoculum of AMF in *Ammophila arenaria* L. (pioneer dune grass). Plant preinoculation with AMF further decreased nematode colonization and reproduction. Nematode suppression by AMF did not occur through a systemic plant response but through local mechanisms. In contrast, Khaosaad et al. (2007) reported that the root infection by *G. graminis var. tritici* was systemically reduced when barley plants showed high degrees of mycorrhizal, *Glomus mosseae*, root colonization, whereas a low mycorrhizal root colonization exhibited no effect on infection. A clear systemic bioprotectional effect depending on the degree of root colonization by the mycorrhizal fungus was established. At a higher mycorrhizal colonization rate the concentration of salicylic acid (SA) was increased in roots colonized by the mycorrhizal fungus but no systemic increase of SA could be measured in nonmycorrhizal roots of mycorrhizal plants, indicating that the systemic bioprotectional-effect against *G. gramminis* is not mediated by salicylic acid. Pozo and Azcon-Aguilar (2007) support the theory mycorrhiza mediated systemic induction towards disease control. They describe the steps involved in the process of mycorrhiza mediated systemic induction. Upon germination, AM fungi grow toward the root and form appresoria at the root surface. At this stage, the plant reacts with an increase in SA levels. (i) In a compatible interaction, SA levels decrease as the fungus colonizes the cortex. (ii) JA biosynthesis occurs in arbuscule containing cells. Priming seems to be the main mechanism operating in mycorrhiza induced resistance. The lack of systemic activation of cellular or biochemical defense mechanisms in mycorrhizas and the stronger defense reactions observed upon pathogen challenge support this hypothesis.

6.2.4.4 Integration of Microbial Bio-Control Agents in IPM

The success of microbial biocontrol agents in plant disease control depends on their efficient integration into a disease management system. This can be achieved by efficient formulation, optimization of delivery system, and integration with other control strategies such as host resistance, combination with fungicides and bactericides, combination with other microbial biocontrol agents, and in strategies that involve prevention of pathogen resistance development towards fungicides and other chemical control.

Fluorescent pseudomonads were first developed as talc based formulation for the treatment of potato seed tubers for growth promotion (Kloepper and Schroth, 1981). Talc based formulation of *Pseudomonas fluorescens* strain Pf1 and Pf2 increased grain yield of pigeonpea besides the control of pigeonpea wilt (Vidhyasekaran et al., 1997). Seed treatment of groundnut and pigeon pea with peat based formulation of *Bacillus subtilis* supplemented with 0.5% chitin or with 0.5% of sterilized *Aspergillus* mycelium controlled crown rot and wilt of groundnut and pigeon pea respectively. It also increased growth promotion even in the presence of inoculum pressure (Manjula and Podile, 2001). Application of talc based strain mixture formulation of fluorescent psedomonads through seed, root, soil and foliage to rice crop suppressed sheath blight disease under field conditions better than individual strains based formulations. The average disease reduction for mixtures was 45.1% compared to 29.2% for individual strains. In addition to disease reduction, strain mixtures increased biomass production and yield compared to individual strains (Nandakumar et al., 2001). Combined application of *Pichia guilermondii* and *Bacillus mycoides* (B16) reduced the infection of *Botrytis cinerea* (Persoon) by 75% on fruits in strawberry plants grown commercially under greenhouse conditions. But the individual application of either antagonist resulted in 50% reduction of strawberry fruit infection. Population of yeast increased when applied as mixture rather than single application (Guetsky et al., 2002). Raupach and Kloepper (1998), reported that *Bacillus subtilis* isolate INA7 when used in combination with *Bacillus subtilis* isolate GBO3 and *Curtobacterium flaccumfaciens* isolate ME1 as seed treatments, demonstrated greater growth promotion and numerically better angular leaf spot control of cucumber where methyl bromide fumigation was used compared with that of nonfumigation. This latter mixture of BCAs is the basis for the BioYield product marketed by Gustafson Inc., Plano, TX.

Formulation can affect many aspects of biocontrol performance, shelf life, and safety. As with any biological system, three parameters that greatly affect success are water, food, and environment. Water activity can profoundly affect survival of biocontrol agents in formulations (Connick et al., 1996). A dry product is less weight to ship and at lower risk of possible contamination. Some biocontrol agents form life stages that are relatively simple to formulate, such as bacterial endospores, yeasts, and the resting-spore stages of many fungi (Fravel, 2005). Delivery systems that are well thought-out as to time and place can greatly reduce the amount of biocontrol agent needed. The time and place to deliver the biocontrol agent depends on the biocontrol agent, the pathosystem, and the cropping system (Fravel, 2005). Steddom and Menge (2001) determined that ten repetitive applications of *Pseudomonas putida* at low concentrations through irrigation water resulted in soil populations similar to those from a single application at a tenfold greater concentration. *Bacillus subtilis* applied 1–5 days before infection by *Cercospora* increased control (Collins and Jacobsen, 2003). A double spray of *Pseudomonas chlororaphis* strain PA23 at the flowering stage reduced *Sclerotinia* stem rot to levels not significantly different from the fungicide treatment (Fernando et al., 2007). Similarly, bacterial application at the cotyledon stage of canola, i.e. the stage most susceptible to pathogen infection, plays an important role in the prevention of blackleg infection (Ramarathnam, 2007). This phenomenon was clearly established in our field study where *B. amyloliquefaciens* strain DFE16 applied at the cotyledon stage suppressed the disease as efficiently as the fungicide which was tested. Bacteria seem to prevent early infection of the cotyledon leaves, reducing the chances for systemic infection, and girdling and cankering of the stem. Populations of *Trichoderma harzianum* (Rifai) on strawberry flowers were half as large when delivered by bumblebees or honeybees than by spray applications, but the bee-delivered inoculum provided better control in a 4-year field study (Kovach et al., 2000). However, we still have a long way to go to standardize delivery system and frequency of application to ensure sustainable disease management.

Integration of *Bacillus*-based biological control agents (BCAs) with disease resistant hosts has proven to be useful in management of several disease problems, particularly where high levels of disease resistance is not available, or where high yielding, highly resistant cultivars are not available. Hervas et al. (1998) showed that suppression of Fusarium wilt caused by race 5 of *Fusarium oxysporum* f. sp. *ciceris* ((Padwick) Matuo et Sato) was greater and more consistent on partially resistant cv. PV 61 with *Bacillus subtilis* isolate GB03 seed treatment than on the more susceptible cv. ICCV 4. In a 3-year study, Larson (2004) showed that a BCA, *Bacillus mycoides* isolate Bm J, provided control of *Cercospora* leaf spot equal to synthetic fungicides as measured by AUDPC on a sugarbeet hybrid that had a moderate level of resistance, but isolate Bm J provided only 41% of the control afforded by four fungicide sprays on the susceptible cultivar.

Today nearly all cotton planted is treated with Kodiak (*Bacillus subtilis* isolate GB03) and fungicides (Brannen and Kenney, 1997). Brannen and Kenney (1997) indicated that combining Kodiak with fungicides provides control of pathogens that are not controlled by available fungicides, and the BCA provides control via colonization of the rhizosphere long after the fungicides have degraded. Brannen and Kenney (1997) suggest that success of Kodiak in the cotton market is due to integration with fungicides. *Bacillus pumilis* isolate 341-16-5 has been used as a seed treatment for the control of sugarbeet damping-off and root rot caused by *Aphanomyces cochlioides* (Drechsler), *P. ultimum*, and *R. solani* in combination with varying rates of hymexazol (Jacobsen, 2004). In 14 location-years of testing, this isolate increased both stand at harvest and yield when combined with 20, 30, or 45 g of hymexazol per 100,000 seed compared with that of hymexazol treatments alone. In addition, the 20-g rate was as effective as the 45-g rate when combined with the BCA. *Bacillus pumilis* isolate 341-16-5 was not as effective as hymexazol when used alone, and the 20-g rate was not as effective as the 45-g rate when used alone. In a study of control of avocado black spot caused by *Pseudocercospora purpurea* ((Cooke) Deighton), Korsten et al. (1997) showed that, in eight location-years of research, *Bacillus subtilis* isolate B246 applied with copper oxychloride or with benomyl and copper oxychloride provided more consistent control than either the BCA or the fungicides alone. The integrated program allowed for fewer fungicide sprays, and Korsten et al. (1997) suggested that the integration of fungicides acted as a safeguard in those years unfavourable to BCA activity. Some heavy metal-resistant mutants of *Trichoderma* spp. selected on heavy metal-rich artificial media were effective antagonists of *Fusarium* spp., *Pythium* spp. and *Rhizoctonia* spp. (Kredics et al., 2001). These mutants might be of value for use with heavy metal containing pesticides, as part of an integrated plant protection system. Combination treatments of *Trichoderma viride* (L4 and S17A) with either tebuconazole or compost enhanced control of *Allium* white rot (AWR) caused by *Sclerotium cepivorum* (Berkeley) and, in some treatments, disease was almost eliminated. Combining S17A and tebuconazole resulted in a similar level of AWR to using tebuconazole alone (Clarkson et al., 2006). By using chemical and biological control measures together, the duration of active disease control will be extended and the chances for the development of fungicide resistance can be reduced.

Integration of BCAs into pesticide resistance management strategies has not been well explored. However, use of different modes of action in sequential fungicide applications is considered a keystone of resistance management programs (Jacobsen, 2004; Koeller, 2004). Since *Bacillus*-based BCAs have modes of action different from that of synthetic chemical fungicides, it is logical that they can be used in fungicide resistance management programs. *Bacillus*-based BCAs have modes of action that include antibiosis, parasitism, and induced systemic resistance (Bargabus et al., 2002; Jacobsen and Backman 1993). Matheron and Porchas (2000) reported on the use of Serenade (*Bacillus subtilis* isolate QST 713) alternated with sulfur (Microthiol 80DF), myclobutanil (Rally 40W), or rifloxystrobin (Flint 50WG) for control of powdery mildew of lettuce. Thus, alternate sprays with the BCA Serenade saved 8.96 to 20.16 kg of sulphur per ha, 139 g ai of trifloxystrobin per ha, or 141 g ai/ha and achieved the same results. In addition, by using different modes of action, Matheron and Porchas (2000) proposed that the BCA contributed to a fungicide resistance management program.

6.2.5 Role of Organic Soil Amendments

Cover crops are typically grown during the off-season with an annual cash crop. Cover crops have usually been turned under prior to planting the cash crop. When they are incorporated into the soil they become a "green manure." Cover crops may or may not have any harvestable yield value. However, they have been demonstrated to reduce erosion (Wall et al., 1991; Creamer et al., 1997), improve the physical characteristics of the soil (Reid and Goss, 1981), and reduce plant diseases (Sumner et al., 1981). Root rot is a major disease complex of beans grown in New York, causing substantial economic losses annually (Abawi et al., 1985). This diseases complex is caused by several pathogenic fungi (*Fusarium solani* f. sp. *phaseoli, R. solani, P. ultimum*, and *Thielaviopsis basicola*) and the plant-parasitic nematode (*Pratylenchus* spp.) individually or in any possible combination. A recent test demonstrated that a previous cover crop of grain rye incorporated as a green manure resulted in the highest bean yield and slightly lower root rot severity ratings. Viaene and Abawi (1998) found that sudangrass was effective, as a green manure, in reducing reproduction of *Meloidogyne hapla* (Chitwood) and, therefore, its damage to lettuce plants. In field microplots filled with organic soil infested with *M. hapla*, incorporation of sudangrass grown as a cover crop from late summer to fall resulted in 20–30% increase in the weight of lettuce planted the following spring as compared to lettuce planted in nematode-infested soil that was left fallow.

Composting is becoming an effective way to manage and recycle municipal and industrial waste. It converts organic wastes into a stabilized form, reduces the volume of waste material, destroys human pathogens, provides a way for recycling valuable plant nutrients, and can be used as an effective and desirable soil organic amendment (Hoitink and Fahy, 1986; Dick and McCoy, 1993). In addition to increasing organic matter of the soil, amending with composts also increases soil microbial populations (Pera et al., 1983; Perucci, 1990), which leads to an improvement of the soil quality. Chen et al. (2000) found that the application of brewery compost reduced root galling severity and egg production of *M. hapla* and increased yield of lettuce by 13% in fumigated soil and 23% in nonfumigated soil.

Common root rot (causal agent *Aphanomyces euteiches* (Drechsler)) is a major disease of commercially grown snap bean (*Phaseolus vulgaris* L.). The disease was suppressed by both fresh and composted paper-mill residuals, but the composted residuals at high rates had the lowest disease incidence (<40%) and produced healthiest plants (Leon et al., 2006). Brassica crops used in crop rotations and as green manures have been associated with reductions in soilborne pests and pathogens. These reductions have been attributed to the production of volatile sulphur compounds through a process known as biofumigation, and to changes in soil microbial community structure (Larkin and Griffin, 2006). Indian mustard was found to be most effective for reducing powdery scab and common scab diseases, whereas rapeseed and canola were most effective in reducing *Rhizoctonia* diseases, thus indicating that Brassica crops have potential for use as green manures for the control of multiple soilborne disease problems.

6.2.6 Role of Push-Pull Strategies in IPM

Push-pull strategies use a combination of behavior-modifying stimuli to manipulate the distribution and abundance of pest and/or beneficial insects for pest management (Cook et al., 2007). The pests are repelled or deterred from this resource (push) by using stimuli that mask host apparency or are repellent or deterrent. The pests are simultaneously attracted (pull), using highly apparent and attractive stimuli, to other areas such as traps or trap crops where they are concentrated, facilitating their elimination. The stimuli for "push" components have been grouped according to whether they are visual or chemical cues, whether they are synthetic or plant- or insect-derived semiochemicals, and whether they are usually used to affect host recognition and selection over a relatively long range (visual cues, synthetic repellents, non-host volatiles, host volatiles, anti-aggregation pheromones, and alarm pheromones) or shorter-range host acceptance (antifeedants, oviposition deterrents, and deterring pheromones). The stimuli for "pull" components include visual stimulants, host volatiles, sex and aggregation pheromones, gustatory and oviposition stimulants (Cook et al., 2007).

6.2.6.1 Push-Pull Strategies in Subsistence Farming

Control of Stem Borers in Maize and Sorghum

Maize (*Zea mays*) and sorghum (*Sorghum bicolor*) are principal crops for millions of the poorest people in eastern and southern Africa, and lepidopterous stem borers, e.g., *Chilo partellus* (Swinhoe), *Eldana saccharina* (Walker), *Busseola fusca* (Fuller), and *Sesamia calamistis* (Hampson), cause yield losses of 10% to 50% (Kfir et al., 2002; Khan and Pickett, 2004). The strategies involve the combined use of intercrops and trap crops, using plants that are appropriate for the farmers and that also exploit natural enemies. The push-pull strategy has contributed to increased crop yields and livestock production, resulting in a significant impact on food security in the region (Khan and Pickett, 2004).

6.2.6.2 Push-Pull Strategies in Intensive Arable Agriculture

Control of *Helicoverpa* in Cotton

Helicoverpa species are polyphagous lepidopterous pests of a wide range of crops. The potential of combining the application of neem seed extracts to the main crop (push) with an attractive trap crop, either pigeon pea (*Cajanus cajan*) or maize (*Z. mays*) ("pull") to protect cotton (*Gossypium hirsutum*) crops in Australia from *Helicoverpa armigera* (Hubner) and *H. punctigera* (Wallengren) has been investigated (Pyke et al., 1987). Trap crop efficiency was increased by application of a sugar-insecticide mix.

Control of *Sitona lineatus* in Beans

Sitona lineatus L., the pea leaf weevil, is a pest of field legumes in Europe, the Middle East, and the United States. Adult feeding reduces leaf area, while larvae damage the nitrogen-fixing root nodules. Commercially available neem antifeedant (push) and synthetic aggregation pheromone 4-methyl-3,5-heptanedione (Blight et al., 1991) released from polythene dispensers (pull) were effective as components of a push-pull strategy for control of *S. lineatus* in field trails using faba beans (*Vicia faba*) (Smart et al., 1994).

6.2.7 *Role of Botanicals in IPM*

Plant products, being indigenous resources, are in use for over a century in India to minimize losses in grain storage due to insect pests. Many plant species show selective action against a number of pests through a variety of biological activities including production of behavior-modifying chemicals such as pheromone analogues, repellents, attractants, antifeedants, direct toxicants and insect growth regulators. Such substances are found in many plants for natural defense from their enemies.

Research designed to discover these defensive mechanisms have led to applications that have been integrated with existing pest management programs.

A number of these plants were recommended for pest control in developing countries including those that were not safe to non-target organisms. However, research on botanicals for pest control has continued during the last two decades mostly on neem, *Azadirachta indica* (Juss) and *Chrysanthemum* sp. Many botanical have been studied extensively for integration with biological control (Rabindra et al., 1997), chemical pesticides (Dhaliwal et al., 2000), host plant resistant (Ragumoorthy, 1996) and safety to natural enemies has been recorded (Arora and Dhaliwal, 1994). Jayakumar et al. (2007) reported the effectiveness of combining plant extracts with antifungal microorganisms in the control of red rot of sugarcane, caused by *Colletotrichum falcatum* (Went). Leaf extracts of *Abrus precatorius* L. and *Bassia latifolia* (Roxb.) and the rhizome extract of *Curcuma longa* L. in combination with *Pseudomonas fluorescens* MD1 effectively controlled the disease in greenhouse and field conditions.

For the management of major viral diseases antiviral principles (AVP's) have been successfully employed. The antiviral principles are successfully used for the management of rice tungro virus (RTV), tomato spotted wilt virus (TSWV), groundnut bud necrosis and chilli mosaic virus. Among the AVP's *Croton sparsiflorus* (Morong.), *Euphorbia thymifolia* L., *Prosopis chilensis* ((Mol) Stuntz) (10%) and dried leaf powder of coconut and sorghum has been employed for the management of TSWV in tomato in field condition. These AVP's caused more than 80% reduction of disease incidence and increased the yield up to 26% over control. (Manickam and Rajappan, 1999). In AVP's treated plants, the bio chemical studies revealed that there is induction of new proteins, which will help to reduce the viral disease incidence. Attempts are being made to locate the genes responsible for the induction of antiviral proteins through application of AVP, and to clone these genes thereby enabling the production of transgenic for the control of viral diseases.

6.2.8 Biopesticides for the Management of Nematodes

Commercially available *Pseudomonas fluorescens* was tested against *Pratylenchus zeae* (Graham) in maize and sorghum, *Heterodera cajani* (Koshi) in pulses; *Rotylenchulus reniformis* (Linford and Oliviera) in castor and papaya and root knot nematode, *M. incognita* in tomato and brinjal under field condition. Seed treatment with *P. fluorescens* @ 10 g/kg of seed was effective in suppressing the population by 61.40% and 58.24% in maize and sorghum respectively and increases the grain yield of maize (69.04%) and sorghum (98.57%). Soil application of *P. fluorescens* at 2.5 kg/ha along with chitin and neem cake was found to be very effective against the rice root nematode *Hirschmanniella oryzae* ((van Breda de Haan) Luc & Goodey) recording 51 percent decrease in root population (Swarnakumari, 1996). In Florida field trials, two Gram-positive PGPR isolates (*B. subtilis* strain GB03 and

Bacillus amyloliquefaciens (*ex* Fukumoto) Priest et al. strain IN937a) in a formulation containing chitin-reduced *Meloidogyne incognita* ((Kofoid and White) Chitwood) galling and improved root condition of bell pepper and muskmelon when added to transplant media at seeding (Kokalis-Burelle et al., 2002, 2003). Eggs of plant parasitic nematodes were reported to be parasitized by fungal bioagents viz., *Paecilomyces lilacinus* ((Thom) Samson), *Verticillium lecanii* ((Zimmermann) Viegas), *V. chlamydosporium, Trichoderma harzianum, T.viride* and *Gliocladium virens* (Miller) (Rao and Reddy, 1992). The mode of action of their destructive activity is due to be enzymatic disruption of egg shell and larval cuticle and also by physiological disturbances brought about by biosynthesis of diffusible toxic metabolites (Morgan-Jones and Rodriguex-Kabana, 1985). *Paecilomyces lilacinus* is the most promising and practicable biocontrol agent for the management of root-knot and cyst nematodes. In cut flowers like carnation, gerbera, gladiolus and asiatic lily, the application of the fungus at 0.5 g/kg soil was found to check the root knot nematode *M. incognita*.

6.3 Examples of Successful IPM Programs from Around the World

Stern et al. (1957) were the first to assemble the various concepts that make up what is now referred to as IPM. They called for the integration of biological and chemical control strategies based on greater knowledge of the ecosystem; science-based monitoring and prediction of pest populations to identify economic thresholds; the augmentation of natural enemies; and the use of selective insecticides. The management of pests is a key issue for profitability of agriculture and for human and environmental health. Undoubtedly, advances in pest management contributed to the 1.9% per annum growth in agricultural productivity in the United States from 1949 to 1991 (Acquaye et al., 2003). The use of chemical pesticides is a common component of pest-management strategies. Expenditure on pesticides in U.S. agriculture increased eight-fold from 1950 to 1999 to $8.8 billion (in year-2000 dollars). Pesticide expenditures rose from 1.6% to 7.5% of total purchased inputs. This increase was widespread across crops and regions (United States Department of Agriculture, Economic Research Service, 2001).

6.3.1 IPM in Germany for the Control of Fungal Leaf Diseases in Sugar Beet

Cercospora beticola (Saccardo) is the primary leaf pathogen of sugar beets in Germany, where economic losses may reach US $1,500/ha (Wolf and Verreet, 2002). Powdery mildew, caused by *Erysiphe betae* ((Vanha) Weltzien), is also common, however, sugar losses (about 5 to 15%) tend to be lower than for *Cercospora* leaf spot (Ahrens and Breustedt, 1984). In the past, sugar beet leaf diseases were often controlled by applying fungicides on fixed-calendar schedules or growth stages. In many cases, these treatments were applied without regard to cultivar resistance or weather conditions. Additionally, management decisions were often adversely affected by poor disease diagnosis. A new approach was needed to provide adequate disease control while effectively reducing the chemical load on the environment. Proper diagnosis is a key component of the IPM program. The implementation and acceptance of the sugar beet IPM model was based on the ability to accurately diagnose foliar diseases and to transmit the disease warning system to the farmer in a user-friendly system. In the past, misidentification of foliar diseases, particularly between leaf blotching caused by *Pseudomonas syringae* and *Cercospora* leaf spot, often resulted in unnecessary fungicide treatments. Symptoms associated with *P. syringae* are already common in June but are temporary and originate from physical injuries such as hail. Fungicide applications are neither necessary nor do they have any effect against the bacterium. Hence, accurate diagnosis at early stages of the epidemic is very important. The most important advantage of the model is the potential for reducing or eliminating fungicide applications. The model also links the fungicide treatment and damage thresholds to develop forecasts of damage risk. The damage threshold alone is not suitable for optimization of timing fungicide applications, because even the new generation of fungicides is not effective in suppressing disease development once the damage threshold is reached. Therefore, there is a need to define special thresholds that allow optimum fungicide efficacy. The yield risk potential forecast of the IPM model takes this into account.

6.3.2 IPM in California

This IPM system focuses on the five major commodities of California, almonds, cotton, oranges, processing tomatoes, and lettuce. Also, it has been a subject of case study by Mullen et al. (2005) which illustrates the impacts of public investment in research and extension in pest management on the economic efficiency of agricultural production and on the risks to human and environmental health. IT also estimates the returns to University of California (UC) investments in pest management in these industries.

6.3.2.1 Almonds

Navel orangeworm (*Amyelois transitella* Walker) is the most significant pest of almonds causing extensive damage to the nuts. In the late 1970s, growers relied heavily on pesticides such as azinphosmethyl and carbaryl but resistance was an emerging problem. Monitoring of pest populations and post-harvest orchard sanitation the removal of mummy nuts to break the breeding cycle have been key components of an IPM package. The cumulative investment in developing and maintaining this IPM package from 1970 to 1999 was $65.3 million. The main benefit has been a reduction in insect damage, totaling $375 million since 1980. Also, a savings of $282 million in the use of pesticides was recognized.

6.3.2.2 Cotton

The cotton IPM program has the typical features of regular monitoring of pest and predator populations based on scientific protocols, and resistance management in the choice of pesticides. The IPM in cotton has been successful in reducing the use of broad-spectrum pesticides by supplementing them with other technologies based on monitoring populations of pests and their predators. The total value of UC research and extension investments in pest management in cotton from 1970 to 1997 compounded forward to 2000 was $162 million. Benefits to the cotton industry from IPM technologies come in the form of pesticide savings.

6.3.2.3 Oranges

The citrus industry in southern California has a long history of successfully employing biological pest control. Morse and Luck (2000) noted that thirteen exotic pests of oranges had been controlled biologically in southern California. The two most important pests of citrus have traditionally been California red scale, *Aonidiella aurantii* (Musk), and citrus thrips, *Scirtothrips citri* (Grafton-Cardwell). The real savings in pesticide expenditures, from the use of biological control agents, compounded forward to 1999, were $66.8 million in Southern California and $5.6 million in the San Joaquin Valley, giving a total benefit stream worth $72.4 million.

6.3.2.4 Processing Tomatoes

The IPM program reduced losses due to worm damage by 40% while annual savings in pesticides to combat nematodes totaled $100 per acre ($40/ha) over 40% of the crop. The value (in year-2000 dollars) of the stream of benefits from 1990 to 1999 from the development of nematode-resistant varieties was $134 million. The benefits from better management of insects and mites between 1981 and 1999 were $48 million. Total benefits amounted to $182 million.

Information-based management strategies have been particularly important for the control of arthropods in California. IPM technologies have allowed growers to make more profitable pest-management decisions, particularly about pesticides, through the use of information about pest populations and knowledge of their interactions with their natural enemies and cultural and chemical control measures.

6.3.3 *IPM Program for Managing Fungal Leaf Blight Diseases of Carrot in New York*

Fungal leaf blight diseases caused by *Cercospora carotae* ((Passerini) Solheim) and *Alternaria dauci* ((Kuhn) Groves et Skolko) occur annually on processing carrot in New York, with growers applying up to eight fungicide sprays to manage these diseases. An integrated pest management (IPM) program involving the use of a 25% disease incidence threshold to prompt the first fungicide application and timing subsequent sprays by monitoring for increases in disease severity and weather forecasts in conjunction with a 10- to 14-day spray interval was evaluated in grower fields in 1997 and 1998 (Gugino et al., 2007). The IPM plots, compared with the grower plots, required two to six fewer fungicide applications but showed no yield reduction. From 1999 to 2004, the IPM program was validated and the effect of crop rotation and carrot cultivar susceptibility also were assessed. Carrot plants growing in fields with 2-year or longer crop rotation intervals reached the 25% disease incidence threshold later in the season and required fewer fungicide applications. The less-susceptible carrot cultivars also reached the 25% disease incidence threshold later, required fewer fungicide applications, and were less severely diseased than more susceptible cultivars. Growers in general are interested in adopting IPM practices (Hollingsworth and Coli, 2001) and reducing fungicide applications, but they must be convinced that the diseases and their resultant losses are prevented by using IPM. Therefore, continued demonstration and outreach regarding the effectiveness of this IPM program for carrot leaf blights is necessary to promote its further adoption among New York carrot growers.

6.3.4 Successful IPM Strategies in Canada

By 1994, the apple ermine moth, *Yponomeuta malinellus* Zeller (Lepidoptera: Yponomeutidae), was a serious pest of apple, which had spread into the commercial apple-producing regions of Okanagon and Similkameen valleys and most of British Columbia, including Washington and Oregon to the south of the border (Cossentine and Kuhlmann, 2000). *Ageniaspis fiscicollis* (Hymenoptera: Encrytidae), has been successfully released and used in the control of the apple ermine moth in British Columbia. The parasitoid is a oligophagous, specific to Yponomeutidae, synchronized with its host species and occupies a wide geographic range (Affolter and Carl, 1986). Apple ermine moth has decreased in areas where *A. fuscicolis* was released, especially in Vancouver island where the moth is consistently found, mean parasitism of *A. fiscicolis* was as high as 23% (Cossentine and Kuhlmann, 2001). Cossentine and Kuhlmann (2007) also note that similar studies were also carried in the USA, for the control of the pest, and recommend that international introductions could be better handled through collaborative classical biological control projects.

Generalist natural enemies can be key members of biological control, and programs would adapt and offer better control of pests that imported generalist predators. Dicyphus Hesperus Knight, is an endemic generalist predator that has been used in the greenhouse tomato crops in Ontario, Quebec and British Columbia (Gillespie et al., 2007). It appears to be particularly useful when tomatoes are grown under lights in winter. In winter, when growers interplant new plant among mature plants, *D. hesperus* moves readily to the new plants and provides control of pests moving from the old plants. It provides excellent control of whitefly and thrips in tomato crops (Gillespie et al., 2007).

Sporothrix flocculosa Traquair, a yeast-like fungus, was isolated from mildew infection sites and found to be an exceptional control agent of powdery mildew on a number of crop plants (Jarvis et al., 2007). Sporodex® performed as well as the best recommended fungicides (such as dodemorph acetate and microfine sulphur) under commercial conditions of greenhouse cucumbers in Ontario, Quebec, USA, Netherlands, France and Greece. It increased yield in cucmber without evident residues and improved the flower quality of roses (Belanger et al., 2002). Its also compatible with other pest control products and is used in integrated pest management systems for greenhouse crops. Sporodex® was registered as a biofungicide in Canada in 2002 and in the USA in 2003 (Jarvis et al., 2007).

In temperate climates, greenhouses, owing to their enclosed structure and highly sophisticated crop production systems, provide the ideal conditions for the implementation of biological control. The stable growing conditions can be manipulated to maintain the populations of the biocontrol agents and reduce the invasion of pests and diseases. By creation of excellent partnerships that brought together Canadian researchers, biological control companies and greenhouse growers organizations, the Canadian greenhouse industry has almost completely transitioned from total chemical control to a balance of biological control and integrated pest management for managing pests of greenhouse vegetables (Shipp et al., 2007).

6.4 Transfer of Technology

There is renewed interest in the use of eco-friendly methods for pest management. The implementation will be possible through appropriate knowledge empowerment in a situation where exploitative practices are still in vogue. The “do how” processes are more relevant. Therefore farmer-led and participatory programs are very essential if desired goals of eco-friendly production and commodity export are to be achieved. Depending upon the cropping systems and agro-ecological zones “tailor-made” programs can be evolved and farmers scientists have to be involved in the production programs. This will enable the farmers to learn methodological skills and develop scientific and durable solutions. To make it as a realistic one, community based IPM program is a prerequisite for the success. Though several FFS programs are organized at national level, the farmers have to be motivated to participate in the program, because without the involvement of the farmers, the program is not going to succeed. Only then the IPM programs can be implemented at local level. Presently in general the cooperation from the farmer’s side at rural level is not satisfactory. In addition, the scientists and extension workers should dedicate themselves for the betterment of the farmers so as to educate farmers not to use excess pesticides and not to pollute environment. The importance of farmer involvement and the success of IPM has been has been proved by the Insecticide Resistance Management Program launched in India (Peshin et al., 2007). The Central Institute of Cotton Research, Nagpur—India (CICR), launched IPM program in ten cotton-growing states of India, called Insecticide Resistance Management (IRM) in 2002, focusing on 26 districts, which between them consume 80% of insecticides for cotton crops (Russell, 2004). IRM based IPM program is directly being implemented by the scientists at Punjab Agricultural University, Ludhiana, India (PAU), so that there is direct information flow from scientists to farmers (from research sub-system to farming sub-system). IRM program is being implemented in Punjab since 2002, covering main cotton-growing areas of Punjab. The majority of the farmers gained knowledge about the major insect-pests, natural enemies, judicious use of insecticides according to good agricultural practices, regular field monitoring, the presence of predators in the cotton fields and their role in insect pest management. The farmers reported the knowledge gain about insect pests, natural enemies, and proper use of insecticides, as the first reward of the IRM program. The farmers possessed pre-training knowledge about timely sowing of cotton crop and its benefits viz-a-viz pest management, but farmers did not gain substantially with respect to the role of cultural practices in management of pests. This could be due to the fact that training program picked up momentum in later stages of crop cycle, when majority of these cultural operations were over. The program needs the same intensity in the initial crop stages as observed 70 days after sowing. The aggressive campaign launched by the project staff to popularize IPM philosophy using all channels of communication acted as a barrier for pesticide agents of chemical companies to lure the farmers into their net. Experimental learning in the “field laboratory” (farmers’ field) will go a long way in making farmers move to higher levels of cognitive domain: comprehension, application, synthesis and evaluation of the IPM practices, with which farmers were not comfortable (Peshin et al., 2007).

6.5 Conclusions

Decline in crop productivity due to the outbreak of pests and diseases, increase in production cost, degradation of natural resources, health hazards and environmental pollution necessitate a paramount shift in production technology. Farmers and agro-based industries could thrive only through the technological innovation that goes in harmony with IPM practices. To achieve technological innovation several researchable issues related to IPM have to be addressed for better adoption of IPM. Issues pertaining to cost benefit analysis of IPM, human health risk assessment, development of improved bioformulations, development of resistant cultivars and the constraints in commercialization of biocontrol has to be addressed for the successful implementation of IPM. However, IPM will come into reality only through the support of Government policies. The policy makers have to be advised to allocate budget for the extensive training, motivation of farmers and promotion of IPM through the establishment of IPM network coordinated by various government and non-governmental agencies. The restructuring of both research and policy issues will pave the way for sustainable agriculture production.

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